ZERO LEAKAGE DESIGN FOR DUCTS AND TUBE CONNECTIONS
FOR DEEP SPACE TRAVEL

GUIDE IN SELECTING DUCT, TUBING AND GASKETING MATERIALS FOR SPACE VEHICLES AND MISSILES

Volume III
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FOREWORD

This is Volume III of a six volume final report covering work accomplished by the Research and Development Center of the General Electric Company, Schenectady, New York from 5 July 1963 to 30 June 1967. This program was sponsored by the Missile and Space Division of the General Electric Company, Philadelphia, Pennsylvania, under National Aeronautics and Space Administration Contract NAS 8-11523 "Zero Leakage Design for Ducts and Tube Connectors for Deep Space Travel."

The six volumes contained in this final report are:

Volume I -- "Fundamental Investigations"

Volume II -- "Connector Concept Studies"

Volume III -- "Guide in Selecting Duct, Tubing, and Gasketing Materials for Space Vehicles and Missiles"

Volume IV -- "New Connector Designs and Testing"

Volume V -- "Tube Connector Design Principles and Evaluation"

Volume VI -- "X-Connector Feasibility Studies"

ACKNOWLEDGEMENT

Several references have been extensively used in compiling this Guide Manual and warrant acknowledgement. The major portion of the material properties data was taken from "The Materials Selector Issue 1963" of Materials in Design Engineering (Reference 1) and "Strength of Metal Aircraft Elements" (Reference 2). Format and data used for the chemical compatibility table was taken from "Material Selection, Process Development, and Preliminary Design" (Reference 3) and expanded by using other references. The work of H. H. Uhlig presented in "Corrosion Causes and Prevention" (Reference 4) was used to a great extent in writing the compatibility section. The propellant safety manual, "The Handling and Storage of Liquid Propellants" (Reference 5) was used extensively in writing the discussion of propellants.

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Section 1

INTRODUCTION

This is Volume III of a six volume report covering work accomplished during the period from July 5, 1963 to June 30, 1967, under NASA Contract NAS 8-11523, "Zero Leakage Design for Ducts and Tube Connections for Deep-space Travel."

OBJECTIVE AND USE OF GUIDE MANUAL

The objective of this guide manual is to present an efficient and compact compilation of useful data to aid designers confronted with the selection of a tube or duct material for missile, rocket, and space vehicle propellant handling and storage applications. This guide manual can be used:

- To determine if a given material is satisfactory for a given set of conditions (Sections 2 and 4). This would be helpful to a designer who has had previous experience with a certain duct material that has performed satisfactorily under a specific set of requirements. When he is confronted with a new set of requirements that are slightly different, this manual will provide him with the information necessary for evaluation of the previous material for the new conditions.

- To search for new material for a given set of requirements (Section 3). In this case, the designer must list the requirements that the unknown material must withstand. He should refer to the material property tables in Section 3 and consider only those materials that meet the specified requirements. A supplemental check should be made in Sections 2 and 4 after a tentative selection is made.

CONDITIONS AND LIMITATIONS

Physical and mechanical properties are given for a specific form, composition, temper, and heat treatment. When a specific case does not match that given here, the designer must interpolate, apply conservative safety factors, search further, or experiment as he sees fit.

Material limitations due to temperature and compatibility with propellants are presented in chart form. Also included is information describing the behavior of materials in a corrosive environment and data is presented pertinent to the selecting of materials for a propellant handling system. In general, the information is valid where:

- there is no flow
- atmospheric pressure and room temperature prevail
- the environment is nuclear free.

It is obvious that almost any use of this data will be an extrapolation. It is then at the designer's option to either accept that extrapolation, search further, or to determine for himself which data exactly fits his problem. The data and accompanying discussions should serve to reduce the number of materials that must be considered.

Section 2

MATERIAL PROPERTIES

The material properties given have been compiled mainly from "Metals Hnadbook" (Reference 6) and the "Materials Selector Issue" of Materials in Design Engineering (Reference 1). Ranges of values are given where available, covering variations reported by investigators for the same alloy. Unless otherwise stated, all properties are for annealed materials, tested in air at room temperature.

Tables I-XII give material properties for metals, metallic gaskets, plastics, and rubbers while Table XIII gives the effect of temperature on ultimate tensile strength.

Figures 1-54 show plots of the effect of temperature on material properties.

Nomenclature for Material Properties Tables

(I)	Izod Impact Test
(C)	Charpy Impact Test
(B)	Brinell Hardness
(VHN)	Vickers Hardness Number
OX	Oxyacetylene Welding
IA	Inert Arc Welding
ER	Electric Resistant Welding
*	A machinability index based on AISI B1112 = 100
**	All percentage values of alloying agents are approximate values.
+	Letter A indicates most favorable, B less favorable, etc., relative to the family of alloys under consideration.
(W)	Hot Working Temperature ^{o}F
(V)	In a Vacuum
(S)	Recommended Service Temperature
F.C.C.	Face Center Cubic
B.C.C.	Body Center Cubic
C.P.H.	Closed Packed Hexagonal

TABLE I MATERIAL PROPERTIES OF METALS - ALUMINUM

	2024-T3	3003-H18	5052-H38	6061-T6
Physical Properties				
Density lb/in^3	0.10	0.099	0.097	0.098
Coef. Lin. Exp. in/in ^{o}F x 10^{-6}	12.9	12.9	13.2	13
Thermal Con. Btu/hr/ft^2/ft/^{o}F	109.2	111	80	99
Mechanical Properties				
Modulus of Elast. psi x 10^6	10.6	10	10.2	10
Torsion Modulus psi x 10^6	4	--	3.85	3.8
Tensile Strength psi x 10^3	64-70	29	39-42	42-45
Yield Strength psi x 10^3	42-50	27	33-37	35-40
Elongation (2 in.) %	7-18	4-10	7-8	12
Hardness	120(B)	55(B)	77(B)	95(B)
Fatigue Str. (1000 psi) 10^6 cyc				
Impact Strength ft-lbs	5-10(C)	--	--	16(C)
Fabricating Properties				
Annealing Temp. ^{o}F	775	775	650	775
Machinability	A$^+$	A	A	A
Weldability	OX, - D$^+$ IA, - B ER, - B	Good relative to aluminum alloys	Good relative to aluminum alloys	Good relative to aluminum alloys
Uses	Aircraft Applications	Chemical equipment, pressure tanks	Aircraft tubing, chemical drums	Pipe, heavy duty structures
Structure	F.C.C.	F.C.C.	F.C.C.	F.C.C.
Composition**	4.5 Cu 1.6 Mg .6 Mn .5 Si .5 Fe .1 Cr .25 Zn AL bal.	2.5 Mn .6 Si .7 Fe .2 Cu .1 Zn AL bal.	2.5 MG .25 Cr .45 Si .1 Fe .1 Cu AL bal.	1 Mg .6 Si .28 Cu .25 Cr .7 Fe AL bal.

TABLE II MATERIAL PROPERTIES OF METALS - BERYLLIUM, COBALT, COLUMBIUM

	Beryllium	Cobalt Haynes 25	Columbium D-31	Columbium F-48
Physical Properties				
Density lb/in^3	0.067	.33	.310	.34
Coef. Lin. Exp. $in/in^{o}F \times 10^{-6}$	6.4	9.3	4.1	3.8
Thermal Con. $Btu/hr/ft^2/ft/^{o}F$	87	13.1	42	24
Mechanical Properties	(annealed)			
Modulus of Elast. psi $\times 10^6$	44	34.2	16.5	25
Tensile Strength psi $\times 10^3$	60-90	146	100	120
Yield Strength psi $\times 10^3$	45-55	67	90	110
Elongation (2 in.) %	2-5	64	--	--
Hardness	--	--	--	275 (VHN)
Fatigue Str. (1000 psi) 10^6 cyc	--	$31(10^8$ cyc)	--	--
Impact Strength ft-lbs	--	--	--	
Fabricating Properties				
Annealing Temp. ^{o}F	1400-2100 (V)	1850-2250 (W)	1950 (V)	2200
Machinability	Difficult because of low ductility.	12*	Similar to stainless steel.	Similar to stainless steel
Weldability	Brazed with Al. alloy or Au. alloy rods.	Good	Electron beam, resistance, brazed.	Welds are brittle
Uses	Nuclear reactors, missiles, aircraft	High temp. app. requiring corrosion resistance.	Space vehicle structures.	Space vehicle structures.
Structure	C.P.H.	C.P.H.	B.C.C.	B.C.C.
Composition**		.1 C, 1.5 Mn, 20 Cr, 10 Ni, 15 W, 3 Fe, 1 Si, Co bal.	10 Ti, 10 Mo, bal Cb.	13.5-16.5 W 4.5-5.5 Mo .85-1.15 Zr

TABLE III MATERIAL PROPERTIES OF METALS - COPPER

	687 (Alum. Brass)	365 (Leaded Mutz)	715 (Cupro-Nickel)
Physical Properties			
Density lb/in^3	0.301	0.304	0.323
Coef. Lin. Exp. in/in $^{o}F \times 10^{-6}$	10.3	11.6	9
Thermal Con. $Btu/hr/ft^2/ft/^{o}F$	58	71	17
Mechanical Properties	(Annealed)	(Annealed)	(Hard)
Modulus of Elast. psi $\times 10^6$	16	15	22
Tensile Strength psi $\times 10^3$	60	54	80
Yield Strength psi $\times 10^3$	27	20	73
Elongation (2 in.) %	--	--	6
Hardness	F-77(R)	F-80(R)	B-85(R)
Fatigue Str. (1000 psi) 10^6 cyc	--	--	--
Impact Strength ft-lbs			
Fabricating Properties			
Annealing Temp. ^{o}F	800-1100	800-1100	1200-1500
Machinability	30*	60	20
Weldability	Silver alloy braze, fair ox.	Fair ox. soft solder excellent.	Soldered, brazed, resistant, ox.
Uses	Condenser, evaporator, heat exch.	Condenser tubes	Resistant to high vel. sea water, chlorides, nitrates, sulfates
Structure	F.C.C.	F.C.C.	F.C.C.
Composition **	77 Cu 2 AL 20.5 Zn	60 Cu 0.6 Pb 39.4 Zn	68.9 Cu 30 Ni 0.6 Mn .5 Fe

TABLE IV MATERIAL PROPERTIES OF METALS - ALLOY STEELS

	4320	4340	4820	5150	8620	8650
Physical Properties						
Density lb/in^3	0.283	0.283	0.283	0.283	.283	.283
Coef. Lin. Exp. in/in $^{o}F \times 10^{-6}$	6.5	6.5	6.5	6.5	6.5	6.5
Thermal Con. $Btu/hr/ft^2/ft/^{o}F$	30	30	30	30	30	30
Mechanical Properties						
Modulus of Elast. psi $\times 10^6$	30	30	30	30	30	30
Tensile Strength psi $\times 10^3$	218-211	284-142 (1)	207-205	312-116 (1)	188-167	282-123 (1)
Yield Strength psi $\times 10^3$	178-173	228-130 (1)	167-184	250-102 (1)	149-120	250-114 (1)
Elongation (2 in.) %	14-13	11-22	14-13	9-22	12-14	11-22
Hardness	429-415(B)	555-293(B)	415(B)	601-241(B)	388-341(B)	555-255(B)
Fatigue Str. (1000 psi) 10^6 cyc	--	--	--	--	--	--
Impact Strength ft-lbs	28-29(I)	18-77(I)	44-47(I)	7-78(I)	26-30(I)	9-78(I)
Fabricating Properties						
Annealing Temp. ^{o}F	1525-1575	1475-1700	1550	1550	1575-1625	1450-1550
Machinability	51*	51	45	55	57	45
Weldability	OX, IA, ER	OX, IA, ER	Ordinarily not welded	OX, IA, ER	OX, IA, ER	OX, IA, ER, Preheating desirable before weld.
Uses	Heavy duty, high strength aircraft tubing.		Heavy duty gears, pump parts.	Shafts, axles, gears.	Aircraft tubing, gears, bearing races.	
Structure	B.C.C.	B.C.C.	B.C.C.	B.C.C.	B.C.C.	B.C.C.
Composition**	0.20 C .55 Mn 1.8 Ni .5 Cr .25 Mo Fe bal.	.4 C .7 Mn 1.8 Ni .8 Cr .1 Mo Fe bal.	.2 C .6 Mn 3.5 Ni .1 Mo Fe bal.	.5C .8 Mn .8 Cr Fe bal.	.2C .8 Mn .6 Ni .5 Cr .2 Mo Fe bal.	.5C .85 Mn .6 Ni .5 Cr .2 Mo Fe bal.

(1) Spread in property between hardened and annealed state.

TABLE V MATERIAL PROPERTIES OF METALS - STAINLESS STEEL

	304L	316	321	347	17-14 Cu Mo Age-Hardenable
Physical Properties					
Density lb/in^3	.29	.29	.29	.29	.287
Coef. Lin. Exp. in/in $^oF \times 10^{-6}$	9.6	9.0	9.5	9.5	8.2
Thermal Con. $Btu/hr/ft^2/ft/^oF$	9.4	9.0	9.3	9.3	
Mechanical Properties					
Modulus of Elast. psi $\times 10^6$	28	28	28	28	
Torsion Modulus psi $\times 10^6$	12.5				
Tensile Strength psi $\times 10^3$	65-85	75-85	70-87	70-92	86
Yield Strength psi $\times 10^3$	25-35	30-35	30-35	30-35	42
Elongation (2 in.) %	55	55	55	50	45
Hardness	B80(R)	B80(R)	B80(R)	B84(R)	
Fatigue Str. (1000 psi) 10^6 cyc					
Impact Strength ft-lbs	110(I)	110(I)	110(I)	110(I)	26(C)
Fabricating Properties					
Annealing Temp. ^oF	1900-2050	1850-2050	2100-2250	1950	2200(W)
Machinability	50	50	55		55
Weldability	Excellent	Excellent	Excellent	Excellent	Arc&Resistance
Uses	General purpose and welded construction.	Processing equipment.	Welded equipment exposed to corrosive conditions.		Parts where good creep, impact strength required.
Composition	.08 C 2 Mn 1 Si 19 Cr 10 Ni Fe bal.	.08 C 2 Mn 1 Si 17 Cr 12 Ni 2 Mo Fe bal.	.08 C 2 Mn 1 Si 18 Cr 10 Ni .4 Ti Fe bal.	.08 C 2 Mn 1 Si 18 Cr 11 Ni 18 Cb-Ta Fe bal.	.12 C, .75 Mn 15.9 Cr, .5 Si, 2 Mo, 14.1 Ni, 3 Cu, .25 Ti, .45 Cb, Fe bal.

Note: Some properties of austentic stainless steels (300 series) are sensitive to minor variations in mechanical and thermal history, chemical composition, and strain rate which affect among other things the amount of transformation of martensite during plastic deformation in tensile tests.

TABLE VI MATERIAL PROPERTIES OF METALS - IRON BASE SUPER ALLOYS

	- Ultra Strength -		- Stainless Steels -	
	Modified H-11	25 Ni	A-286	19-9 DL
Physical Properties				
Density lb/in^3	.281	.295	.286	.287
Coef. Lin. Exp. in/in °F x 10^{-6}	7.4	6.3	10.3	10
Thermal Con. Btu/hr/ft^2/ft/°F	16.6		8.86(302°F)	12.2(1200°F)
Mechanical Properties				
Modulus of Elast. psi x 10^6	30	24	29	29.5
Torsion Modulus psi x 10^6			11.5	
Tensile Strength psi x 10^3	295-311	319	130-150	114
Yield Strength psi x 10^3	241-247	284	85-100	71
Elongation (2 in.) %	6.6-12	8	15-25	41
Hardness				
Fatigue Str. (1000 psi) 10^6 cyc	130-135		38 (10^8 cyc.)	81 (10^8 cycles)
Impact Strength ft-lbs	15-22(C)		24(C)	46(C)
Fabricating Properties				
Hot Working Temp. °F	1700-2100	1500-2250	1700-2150	1200-2150
Machinability	Readily machined in annealed condition.		27	40
Weldability	Fusion weld with shield arc; pre-heat 1000°F, post-heat 600°F.	Coated elect. inert gas; post weld heat treat. to restore properties.	Limited data.	Excellent
Uses	Aircraft and missile housing.	Parts require high strength weight ratio and toughness.	Excellent up to 1300°F in all atmos. in jet engines.	Resistant to acids, exhaust gases in missiles and jet engines.
Composition	.4C, .35 Mn, 1Si, .45V, 5Cr, 1.4Mo, Fe bal.	.006C, .2AL, 25Ni, .17Si, 1.3Ti, .12 Mn, .5Cb, Fe bal.	.08C, 1.35Mn, .95Si, 15Cr, 26Ni, 1.25Mo, 2.15Ti, 3V, .2Al, .003B, Fe bal.	.32C, 18.5Cr, 1.15Mn, .55Si, 9Ni, 1.4Mo, 1.35W, .4Cb &ta, .25Ti, .15Cw, Fe bal.

TABLE VII MATERIAL PROPERTIES OF METALS - NICKEL

	A (200)	Duranickel (Hot Rolled)	Inconel X (750)	Hastelloy-X	Monel (Full Harden Strip)	Rene '41
Physical Properties						
Density lb/in^3	0.321	0.298	0.30	0.30	.319	0.30
Coef. Lin. Exp. in/in^{o}F x 10^{-6}	7.4	7.2	9.2	9	7.8	6.7
Thermal Con. Btu/hr/ft^2/ft/^{o}F	36	10.7-11.2	13	12	15	11.7
Mechanical Properties						
Modulus of Elast. psi x 10^6	30	30	31	28.6	26	31.8
Torsion of Modulus psi x 10^6			--			
Tensile Strength psi x 10^3	55-75	90-120	155-162	114	100-140	206
Yield Strength psi x 10^3	15-30	35-60	92-100	52.2	90-130	154
Elongation (2 in.) %	55-40	50-30	20-24	43	15-2	14
Hardness	B-64(R)	B-90(R)	209(B)		B98(R)	
Fatigue Str. (1000 psi) 10^8 cyc.	30 50	51	60		35-57	
Impact Strength ft-lbs			38-40(C)	33(I)		
Fabricating Properties						
Hot Working Temp. ^{o}F	1200-2300	1600-2300	1900-2225	1800-2200	1700-2150	2150-1850
Machinability			15			---
Weldability	inert gas, metal arc, silver & copper braze	metallic arc inert gas, metal arc, resistance	satisfactory	excellent	metal arc, inert gas, tungsten arc, ox, ER.	good
Uses	good resist. to chlorides & caustic soda	parts requiring corrosion resistance and strength	jet engine and high temp. str.	missile parts,	parts requiring good strength, ductility, corrosion resist.	jet engines, missile, furnaces where high temp. corrosion resist. is vital
Structure	F.C.C.	F.C.C.	F.C.C.	F.C.C.	F.C.C.	F.C.C.
Composition	99.5 Ni	94Ni, 4.5AL, .15C, .05Cu, .25Mn, .5Ti, .15Fe, .55 Si.	.05Cu, 15Cr, 7Fe, .75AL, .4Si, 2.5Ti, .5Mn, .05C, .007S, .9Cb, bal Ni	2Co, 21Cr, 9Mo, .15W, 18Fe, .1C, .1Si, 1 Mn Ni bal	66Ni, .12C, .9Mn 1.35Fe, .005S, .15Si, 31.5Cu.	18-20Cr, 1.4AL 10Co, bal Ni 9-10Mo 5Fe .1C .5Si .1Mn 3.1Ti

TABLE VIII MATERIAL PROPERTIES OF METALS - TITANIUM

	Unalloyed	6 AL-4 V	13 V-11 Cr-3 AL
Physical Properties			
Density lb/in^3	0.163	0.160	.175
Coef. Lin Exp. $in/in^{o}F \times 10^{-6}$	5.8	5.8	5.2
Thermal Con. $Btu/hr/ft^2/ft/^{o}F$	9.8	4.3	4.3
Mechanical Properties			
Modulus of Elast. psi $\times 10^6$	15-16	15-17.5	14.5-16
Torsion Modulus psi $\times 10^6$		6.2	
Tensile Strength psi $\times 10^3$	60-100	130-145	190-240
Yield Strength psi $\times 10^3$	40-95	120-130	170-220
Elongation (2 in.) %	15-25	5-10	5-10
Hardness	C29(R)	C35(R)	
Fatigue Str. (1000 psi) 10^6 cyc.	6-7 (10^8 cyc)	50	50-55
Impact Strength ft-lbs		15-25(C)	5-15(C)
Fabricating Properties			
Annealing Temp. ^{o}F	850-1250	1350	1450
Machinability	excellent	good	good-exc.
Weldability	formability	formability	formability
Uses	parts require high form., good str/wt ratio	high str/wt ratio str., good form., weld	parts require very high str/wt ratio
Structure	C.P.H.	C.P.H.	C.P.H.
Composition		6 AL 4 V Ti BAL	13 V 11 Cr 3 AL Ti BAL

TABLE IX MATERIAL PROPERTIES OF METALS - MAGNESIUM, TANTALUM, ZIRCONIUM

	Magnesium ZK60A-T 5	Tantalum Unalloyed	Tantalum 10W	Zirconium (Cold Worked)
Physical Properties				
Density lb/in^3	.066	.60	.608	.237
Coef. Lin Exp. in/in^{o}F x 10^{-6}	14	2.5		3.1
Thermal Con. Btu/hr/ft^2/ft/^{o}F	68-70	96.6		
Mechanical Properties				
Modulus of Elast. psi x 10^6	6.5	27	21	14
Torsion Modulus psi x 10^6	2.4			
Tensile Strength psi x 10^3	42-50	60	160	64
Yield Strength psi x 10^3	38-40	48	158	53
Elongation (2 in.) %	11-14			24
Hardness	82(B)	155(VHN)	250(VHN)	B89(R)
Fatigue Str. (1000 psi)10^6 cyc.	17-23			
Impact Strength ft-lbs	3(C)			
Fabricating Properties				
Annealing Temp.	300-500$^{(w)}$	2200-2400	2700	1200-1450
Machinability	excellent formability 500	similar to stainless steel with tendency to gall		
Weldability	electrical resistance	weldable by TIG, electron beam and resistance		weld under inert atm., brazed & soldered
Uses	aircraft and missile parts.	acid resis. chemical equip., missiles, rockets	rocket nozzle, heat shields.	chemical plant equipment.
Structure	C.P.H.	B.C.C.	B.C.C.	C.P.H.
Composition	5 Zn .45 Zr bal Mg		10 W Ta Bal.	2 Hf bal Zr

TABLE X MATERIAL PROPERTIES OF METALLIC GASKETS

	Indium	Lead	Alum. 1060-0	Alum. 1060-H/8	Copper	Nickel
Physical Properties						
Density lb/in^3	0.264	0.41	0.098	0.098	.321	.321
Coef. Lin. Exp. in/in^{o}F x 10^{-6}	18.3	16.3	13.1	13.1	9.35	7.4
Thermal Con. Btu/hr/ft^2/ft/^{o}F	13.8	20	135	135	226	35
Mechanical Properties						
Modulus of Elast. psi x 10^6	1.57	2	10	10	17	30
Tensile Strength psi x 10^3	0.380	2.15-3	10	19	32-65	50-80
Yield Strength psi x 10^3	--	1.18-1.38	4	18	10-50	10-30
Elongation (2 in.) %	22	22-57	43	6	4-50	50-30
Hardness					40-95F(R)	40-65F(R)
Fatigue Str. (1000 psi) 10^6 cyc.						
Impact Strength ft-lbs	0.9(B)	71-84 special 1/2" ball-30Kg wt. 30 sec	19(B)			120 (I)
Fabricating Properties						
Annealing Temp. ^{o}F	353(melting point)	618 melt. point	650	650	700-1200	1500
Machinability			good formability			
Weldability		gas welded	good welding	characteristics	good	soft soldered, silver brazed ox. er.
Uses	alloy agent to improve corrosion resistance reactors	chemical equip.	good resist. to corrosion	chemical processing, marine eq.		
Structure	F.C. Tetragonal	F.C.C.	F.C.C.	F.C.C.	F.C.C.	F.C.C.
Composition	99.97% pure	99.9% pure	99.6AL	99.6AL	99.95Cu	99.4 Ni

TABLE XI MATERIAL PROPERTIES OF PLASTICS

	ABS (Medium Impact)	Chlorinated Polyether	KEL-F (PTFCE)	Teflon (PTFE)	Teflon FEP	6 Nylon	Vinylidene Chloride
Physical Properties							
Specific gravity	1.06-1.07	1.4	2.1-2.15	2.1-2.3	2.14-2.17	1.14	1.68-1.75
Coef. of Exp. 10^{-5} psi ^{o}F	3.2-4.2	4.4	3.88	5.5	8.3-10.5	4.6-7.1	8.78
Mechanical Properties							
Modulus of Elas in tension 10^{5} psi	3.7-4.0		1.8	.38-.65	.5-.7	1.5-3.6	.7-2.0
Tensile Strength 1000 psi	7.5-8.5	6	4.6-5.7	2.5-3.5	2.5-3.5	10.2-11.3	15-40
Elongation (2 in.) %	5-20	130	125-175	250-350	300-390	300	20-30
Hardness (Rockwell)	R115-118	R100	R110-115	J 75-95	D55	R103-111	M50-65
Impact Str. (Izod) ft-lb/in	1.3.3.0	33	3.5-3.6	2.5-4.0	No break	1.5-3.5	2-8
Heat Distortion Temp. ^{o}F (264psi) (ASTM D-648)	150-225	285 (66psi)	167	132	124	145	130-150
Useful Temp. Range ^{o}F	-40 to 250	to 300	-400 to 400^{o}F	-450 to 500	-450 to 400	to 250	to 200
Chemical Name	Acrylonitrite Butadiene-Styrene	As Above	Polytrifluoro-chloroethylene	Polytetrafluoro-ethylene	Fluorinated Ethylene Propylene	Polyamides	As Above
Uses	Pipe, lawn & garden equip.; refrigerator linings.	Valves, pump parts, tank linings, pipe.	Chemical pipes, gaskets, pump parts, tank liners, valve diaphragms.	Chemical pipes, valves & valve liners, gaskets, packings.	Valve linings, corrosion resistant and nonadhesive coatings.	Bearings, gears, tubing, pipe.	Extrusion: gasket rods, valve seats, flexible chemical tubing and pipe.
Chemical Resistance		Resistant to organic and inorganic acids except fuming nitric and sulfuric.	Impervious to corrosive chemicals.	Inert to most chemicals and solvents with the exception of alkali metals. Halogenated solvents at high temperatures and pressures have some effect.		Resists petroleum oils, greases, alkalis, esters, ketones, attacked by mineral acids.	Excellent to all acids & most common alkalis.

TABLE XIII EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH*

°F	Percentage of Ultimate Strength at Room Tempeature -400	-300	-200	0	R.T.	200	400	600	800	1000	1500	2000
ALUMINUM												
2024 T3	150	118	108	100	100	97(L)	82(S) 24(L)	22(S) 10(L)	-	-	-	-
3003-H18	-	138	120	102	100	-	-	-	-	-	-	-
5052-H38	178	138	116	100	100	97(L)	65(S) 55(L)	20(S) 16(L)	8	-	-	-
6061-T6	145	122	114	102	100	91(L)	64(S) 42(L)	22(S) 8(L)	-	-	-	-
STAINLESS STEEL												
304L	264	240	200	110	100	85	79	75	72	64	25	
316	235	204	170	106	100	95	87	80	72	65	31	
321	265	230	205	111	100	95	89	81	74	66	24	
347	235	206	180	108	100	87	76	73	70	65	26	
17-14 CuMo					100					85(900°F)	39	
A-286(LS)	-	137	128	103	100	98	96	92	88	82	22	
19-9DL					100	94	88	85	80	68	24	
Alloy Steels (4000 series)		123	117	100	100	97	93	86	75	51		
NICKEL												
Nickel A	157	140	126	102	100							
Rene' 41					100					99	61	27(1700°F)
Duranickel												
Inconel-X		172	160	102	100	99	98	96	91	83	34	
Hastelloy-X					100	100	98	95	91	82	45	20(1800°F)
Monel		128	119	102	100							
TITANIUM												
Unalloyed (C)	196	170	147	107	100	78	56	44	35	26		
6 AL-4V (C)		160	134	101	100	90	81	76	67	54		
13V-11Cr-3AL					100	93	89	86	75	47		
Tantalum		200	150	100	100	95	84	80	65	57	42	32
Columbium F48					100	98	95	91	87	83	70	52
Columbium D-31					100	94	85	76	68	70	64	35
Haynes 25		146	135	103	100	95	88	82	77	68	31	13.7
Beryllium					100	97	90	81	68	48	20(1200°F)	
Magnesium ZK60A-T5	147	141	132	102	100							
Copper (pure)	194	155	134	103	100							
Copper 365 (leaded mutz)		130	115	100	100							
Modified H-11					100			90(500°F)	83	70		
Zircomium	-	178	156	105	100	85	51	41	32	-	-	-
Lead	300	183	167	100	100							
Teflon		400	350	100	100							
Kel-F		260	260	115	100							

*All exposures for 1/2 hour unless otherwise noted.

Explanation of Symbols

(S) Tested at temperature after 1/2 hour exposure.
(L) Tested at temperature after 10,000 hours exposure.
(C) Values independent of time for time between 1/2 to 100 hours.
(LS) Tested at temperature after 10,000 hours exposure.

TABLE XII MATERIAL PROPERTIES OF RUBBERS

	Neoprene (Chloroprene)	Silicone (Polysiloxane)	Viton, Fluorel (Vinylidene Fluoride Hexafluoropropylene	Hypalon (Chlorosulfonated Polyethylene)
Specific Gravity	1.25	1.1-1.6	--	1.18
Coef. of Thermo. Exp. (cubical) 10^{-5} per ^{o}F	34	45	--	27
Tensile Str. (Pure Gum)	3000-4000	600-1300	72000	4000
Elongation (Pure Gum)	800-900	100-500	7350	600
Hardness (Durometer)	A40-A95	A30-90	A60-90	A45-95
Tear Resistance	Fair to Good	Poor	Fair	Good
Min. Rec. Ser. Temp. ^{o}F (S)	-40	-120	-50	-40
Max. Rec. Ser. Temp. ^{o}F (S)	240	550	450	300
Chemical Resistance				
Oxidation	Excellent	Excellent	Excellent	Excellent
Heat Aging	Excellent	Excellent	Excellent	Excellent
Alphatic Hydrocarbons	Good	Good	Excellent	Good
Aromatic Hydrocarbons	Fair	Poor	Excellent	Fair
Oxygenated, Alcohols	Very Good	Excellent	Poor	Excellent
Oil, Gasoline	Good	Poor	Excellent	Good
Concentrated Acids	Good	Good	Good	Excellent
Permeability to Gases	Low	Poor	---	Low
Water Swell Resistance	Fair - Good	Excellent	Excellent	Fair - Good
Uses	Flexible Petroleum tubes & hoses, chemical tank liners.	Seals, gaskets, diaphragms, duct work.	Critical seals, gaskets, diaphragms, flexible mounts, for service in chemical and thermal environments.	Flexible chemical and petroleum tubes and hoses, tank linings.

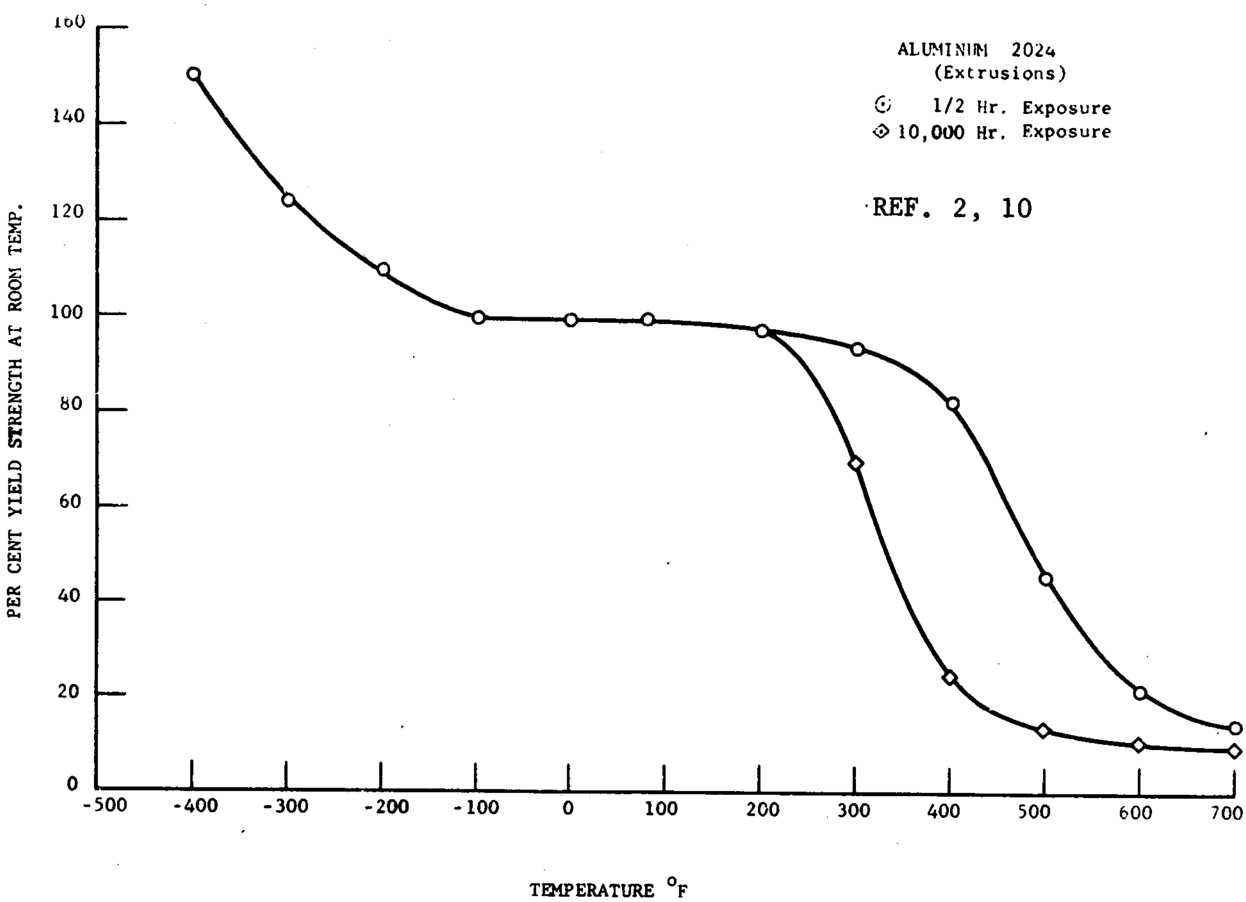

Figure 1 Yield Stress as a Function of Temperature - Aluminum 2024

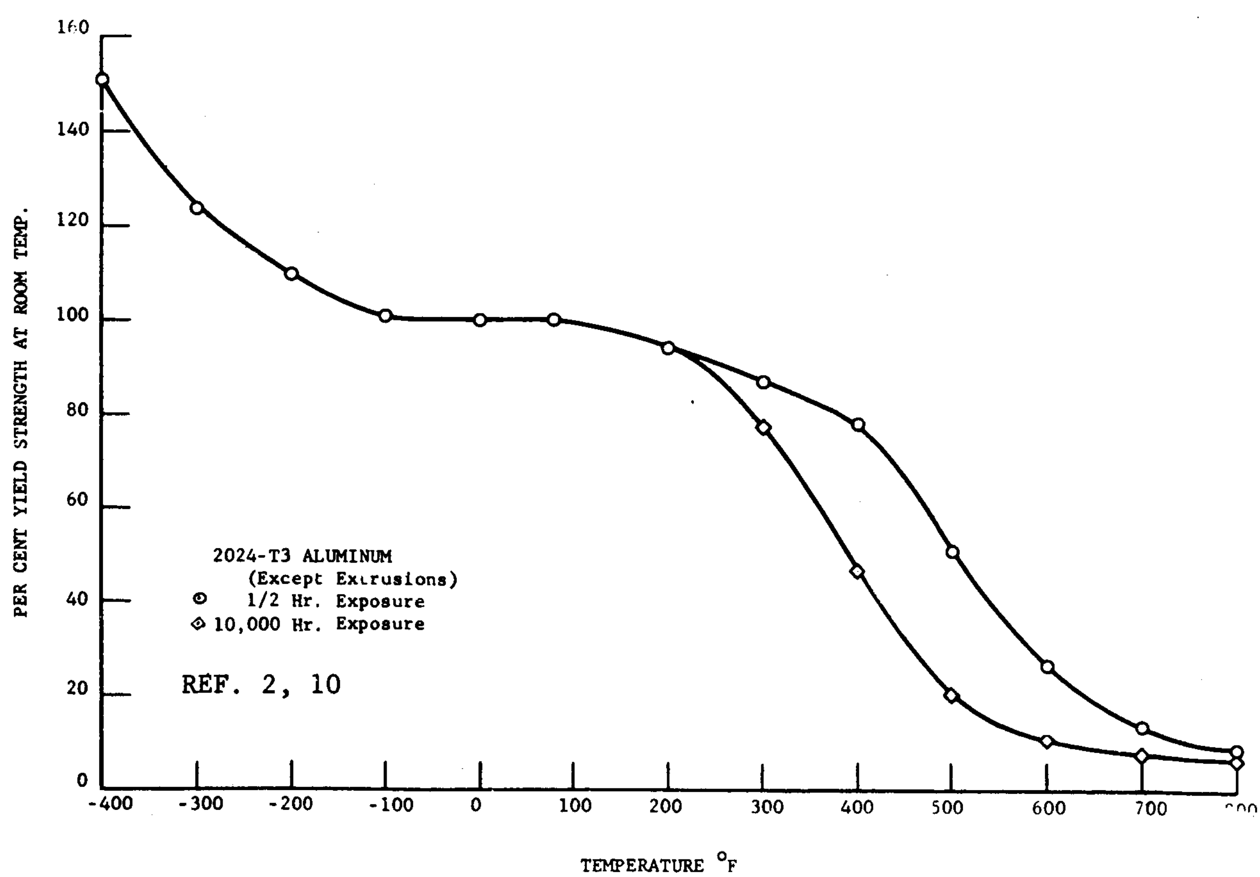

Figure 2 Yield Stress as a Function of Temperature - Aluminum 2024-T3

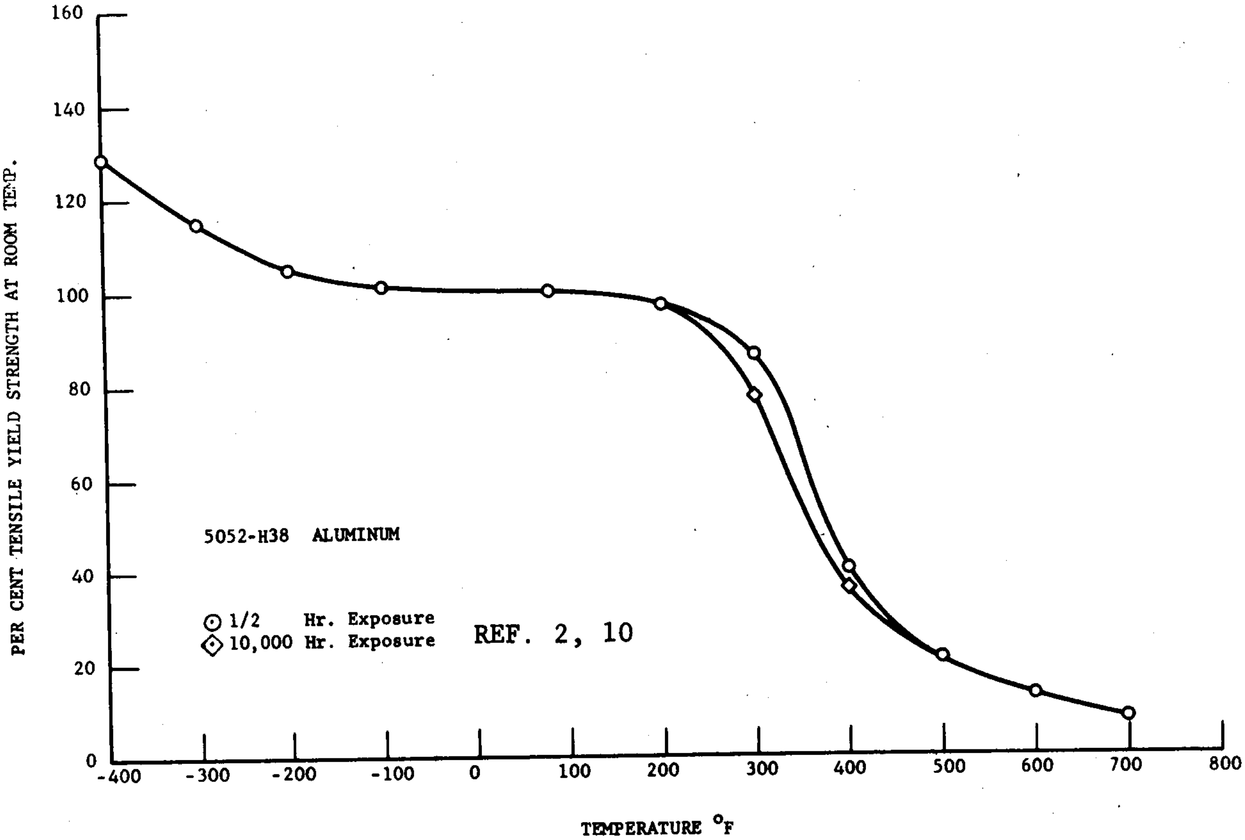

Figure 3 Yield Stress as a Function of Temperature - Aluminum 5052-H38

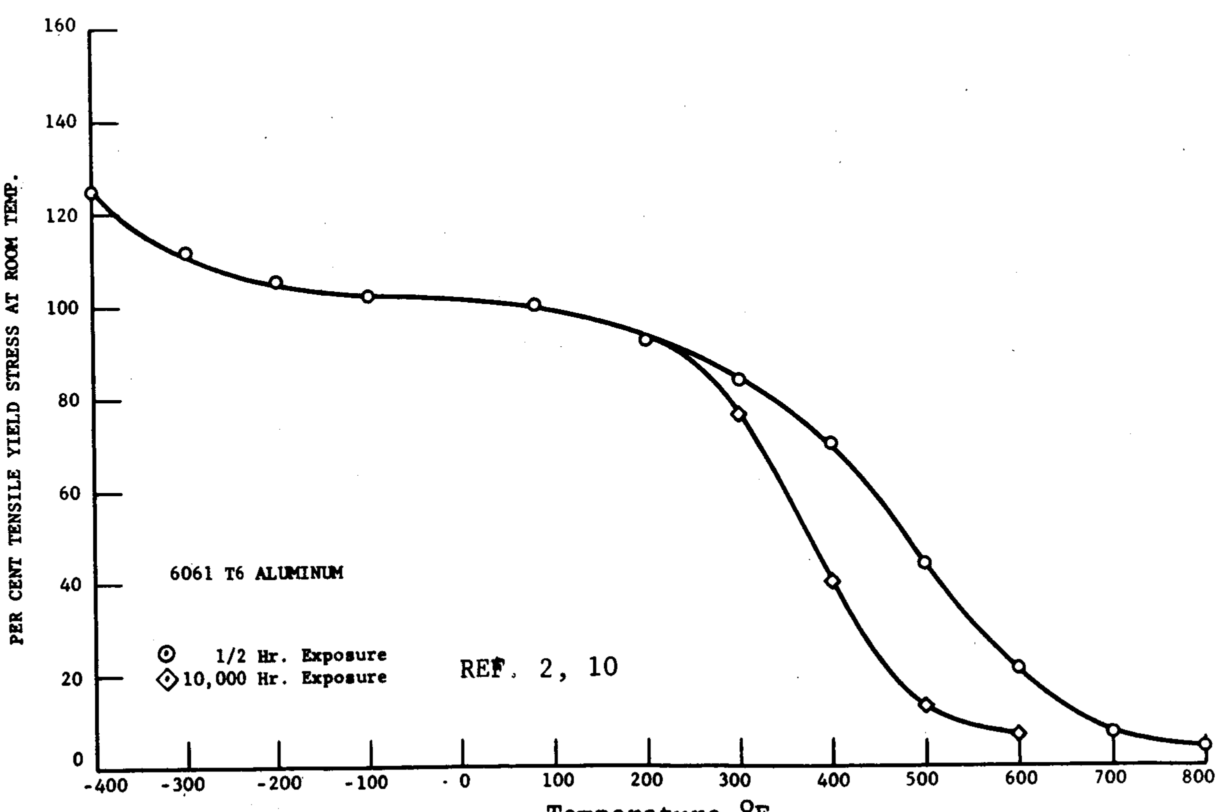

Figure 4 Yield Stress as a Function of Temperature - Aluminum 6061 T6

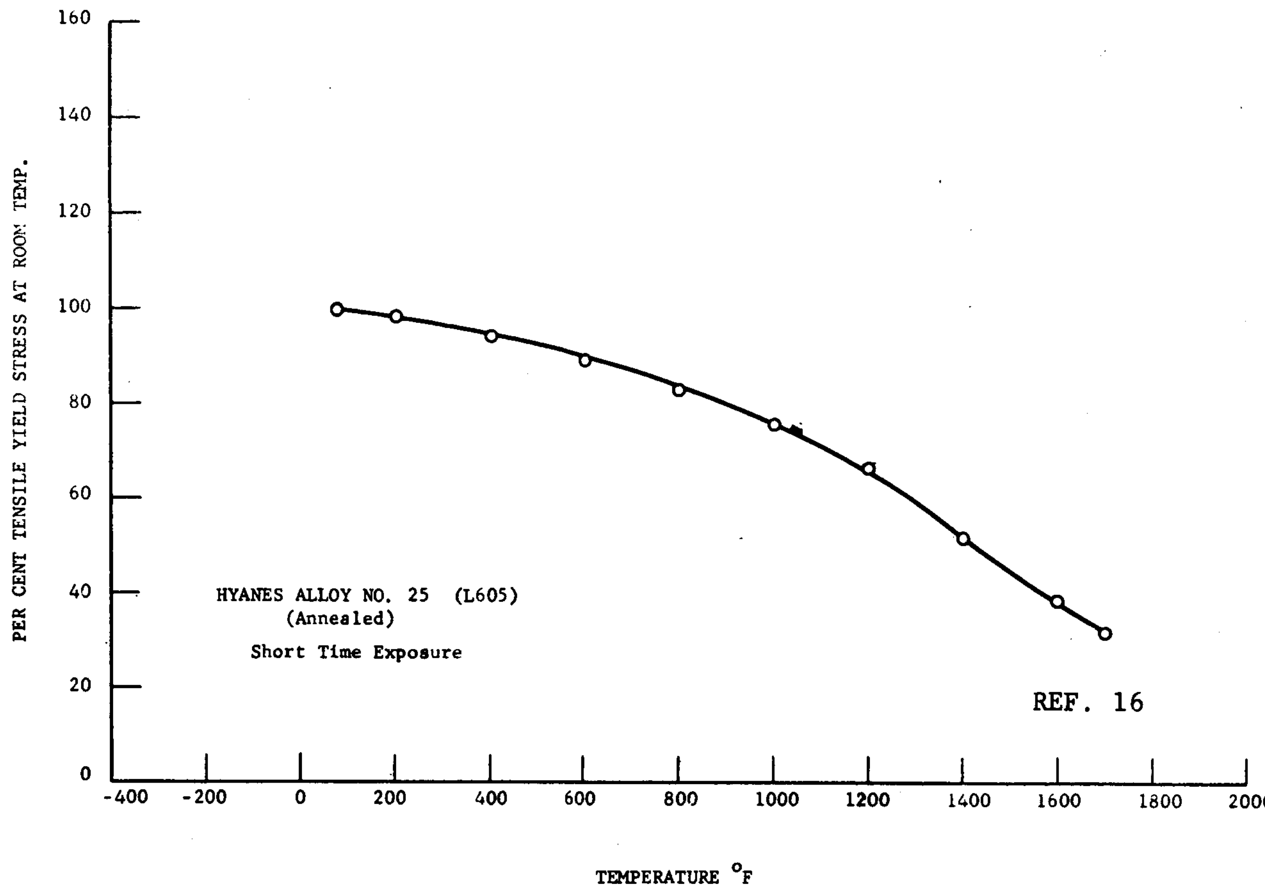

Figure 9 Yield Stress as a Function of Temperature - Hyanes Alloy No. 25 (L605)

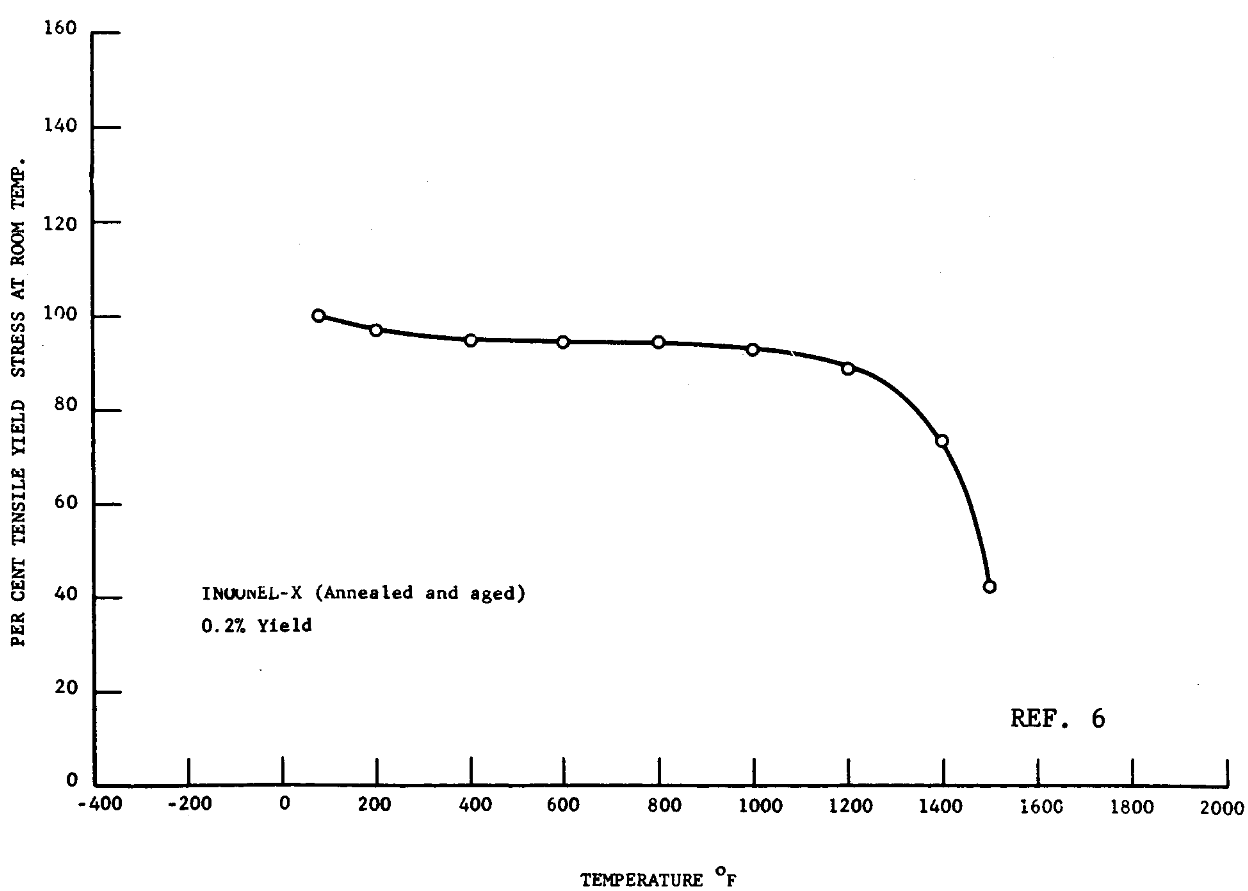

Figure 10 Yield Stress as a Function of Temperature - Inconel-X

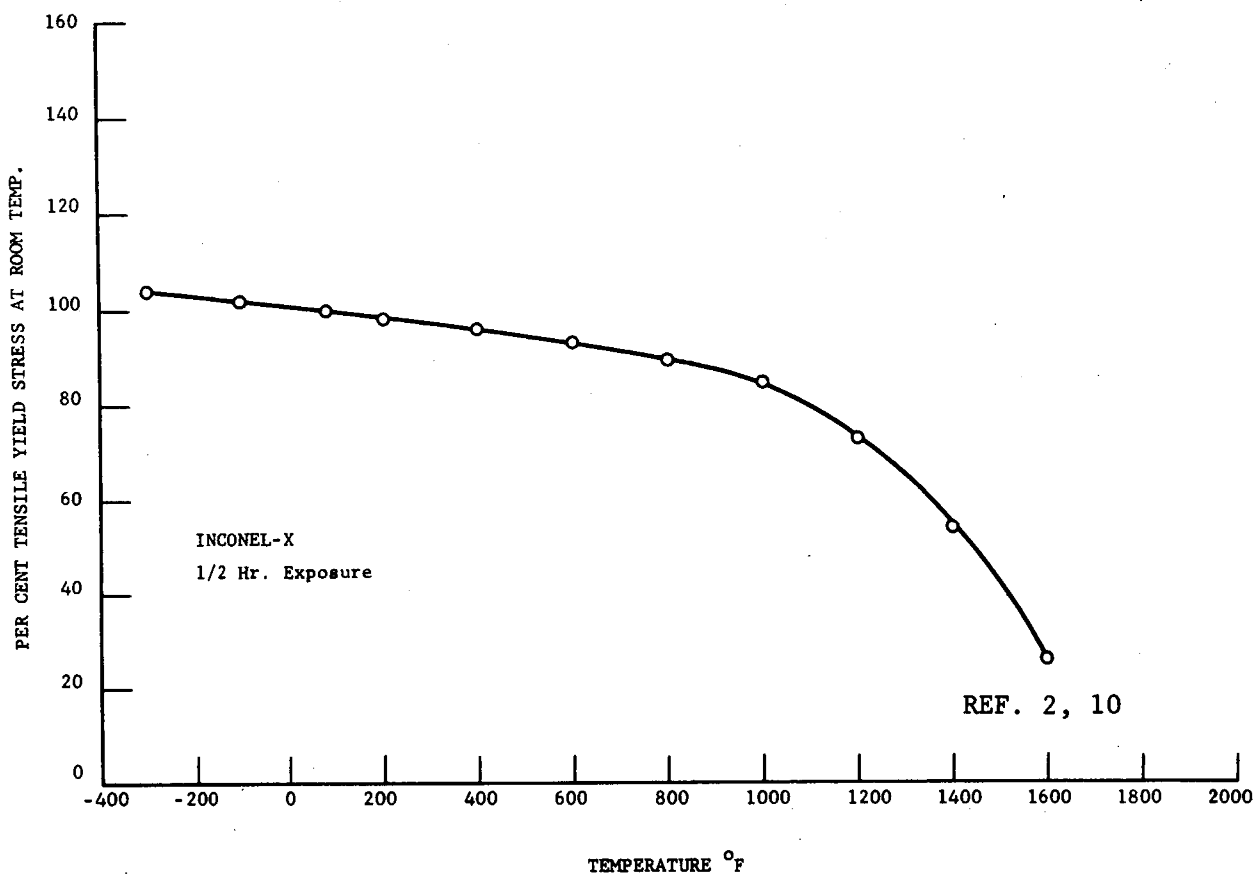

Figure 11 Yield Stress as a Function of Temperature - Inconel-X

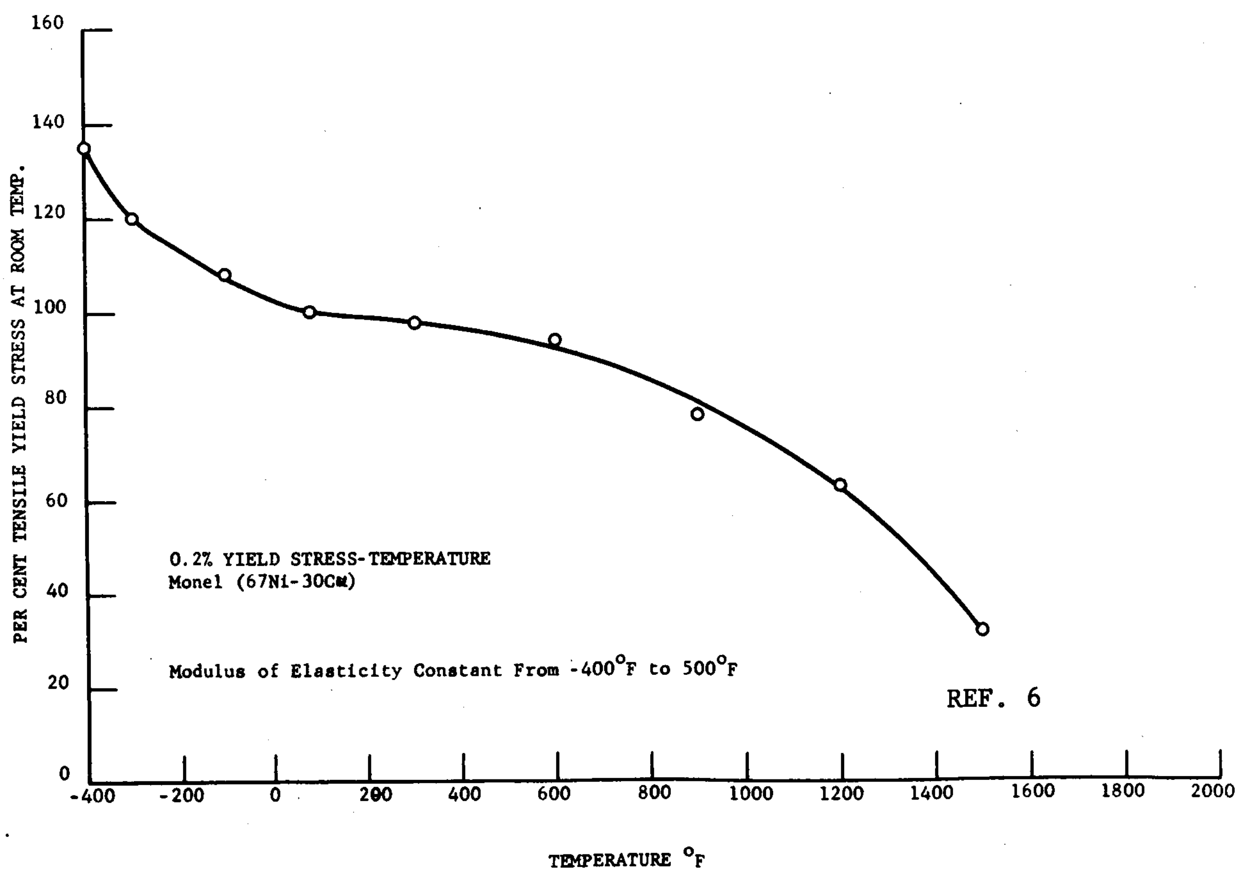

Figure 12 Yield Stress as a Function of Temperature - Monel (6/Ni-30CM)

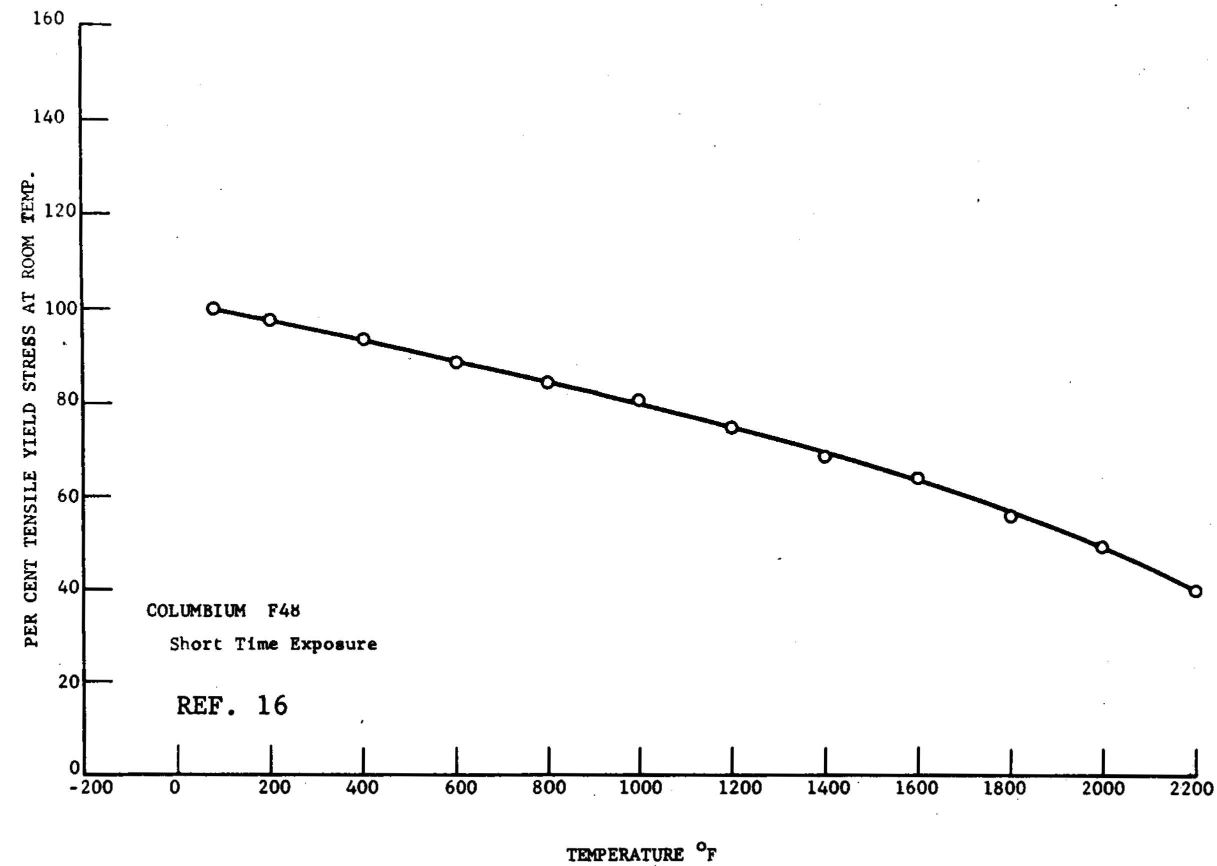

Figure 7 Yield Stress as a Function of Temperature - Columbium F48

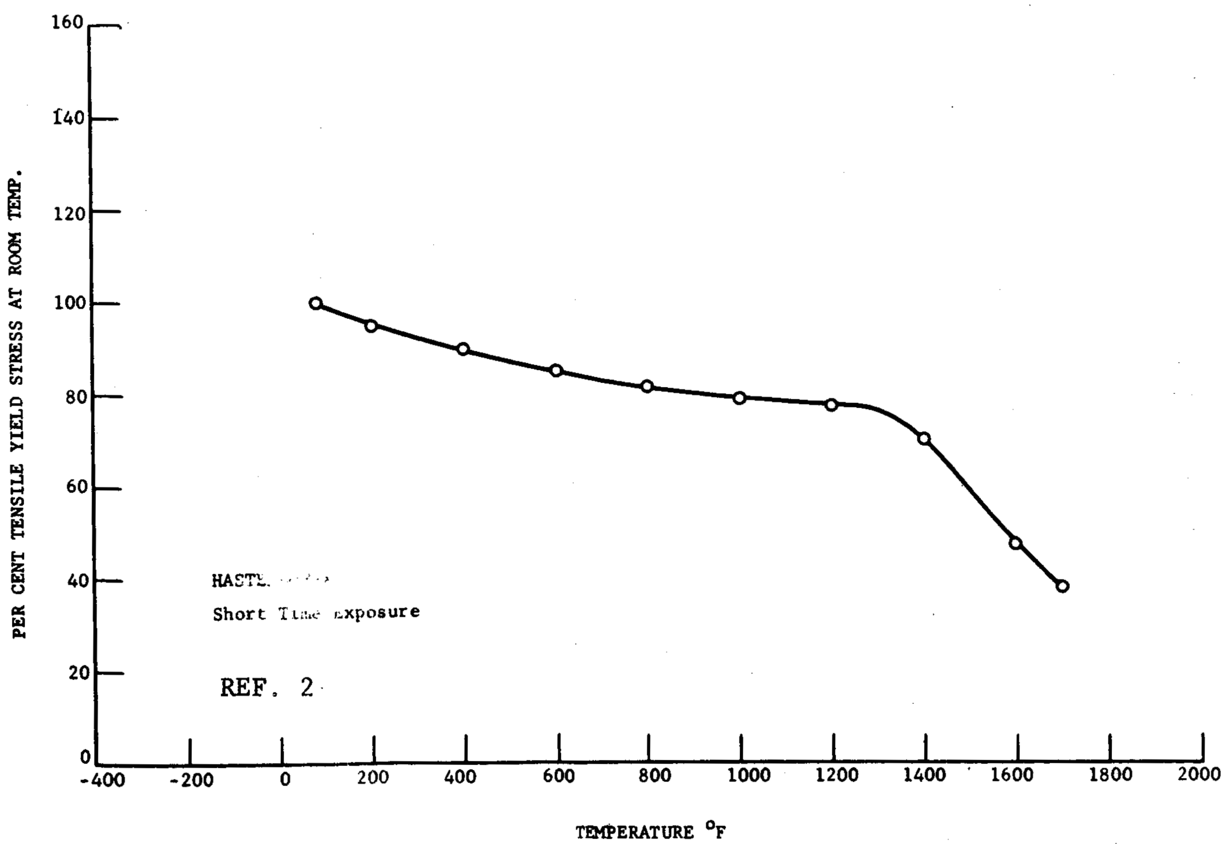

Figure 8 Yield Stress as a Function of Temperature - Hastelloy-X

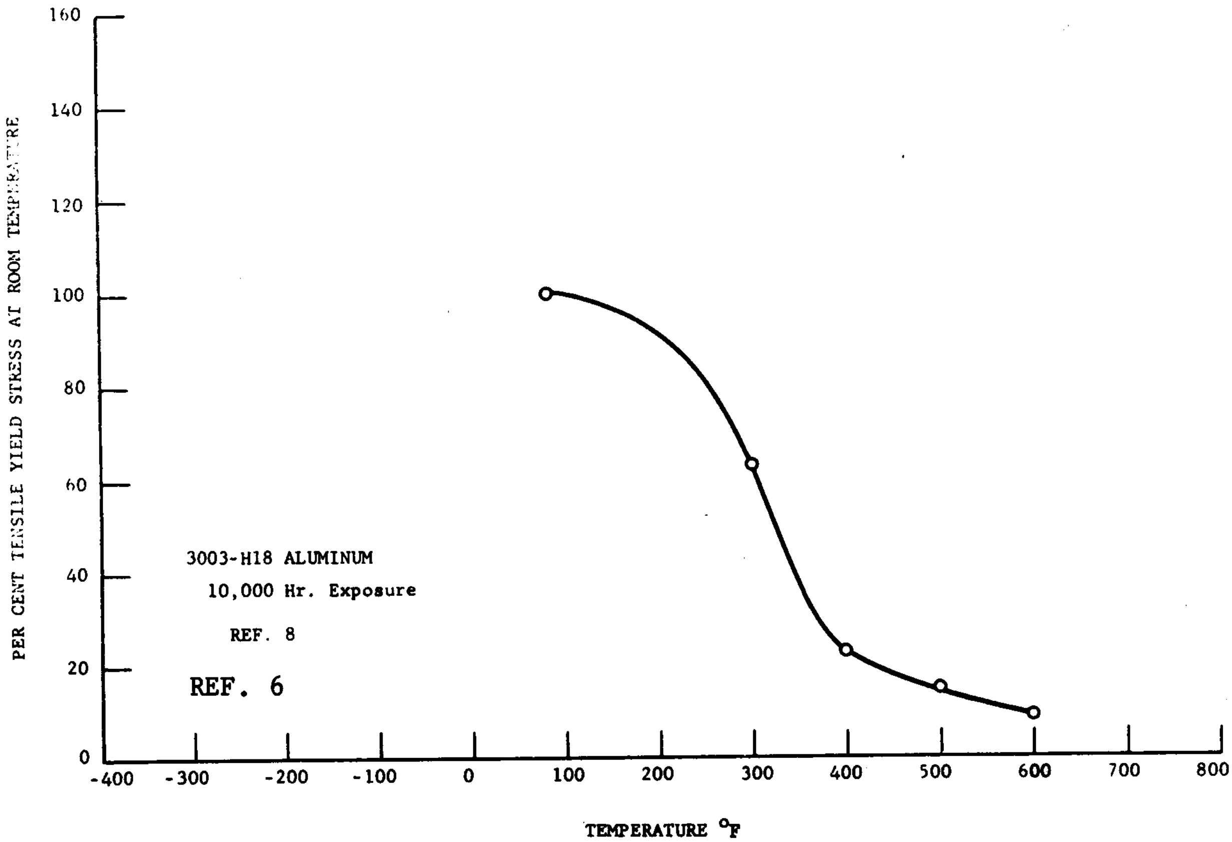

Figure 5 Yield Stress as a Function of Temperature - Aluminum 3003-H18

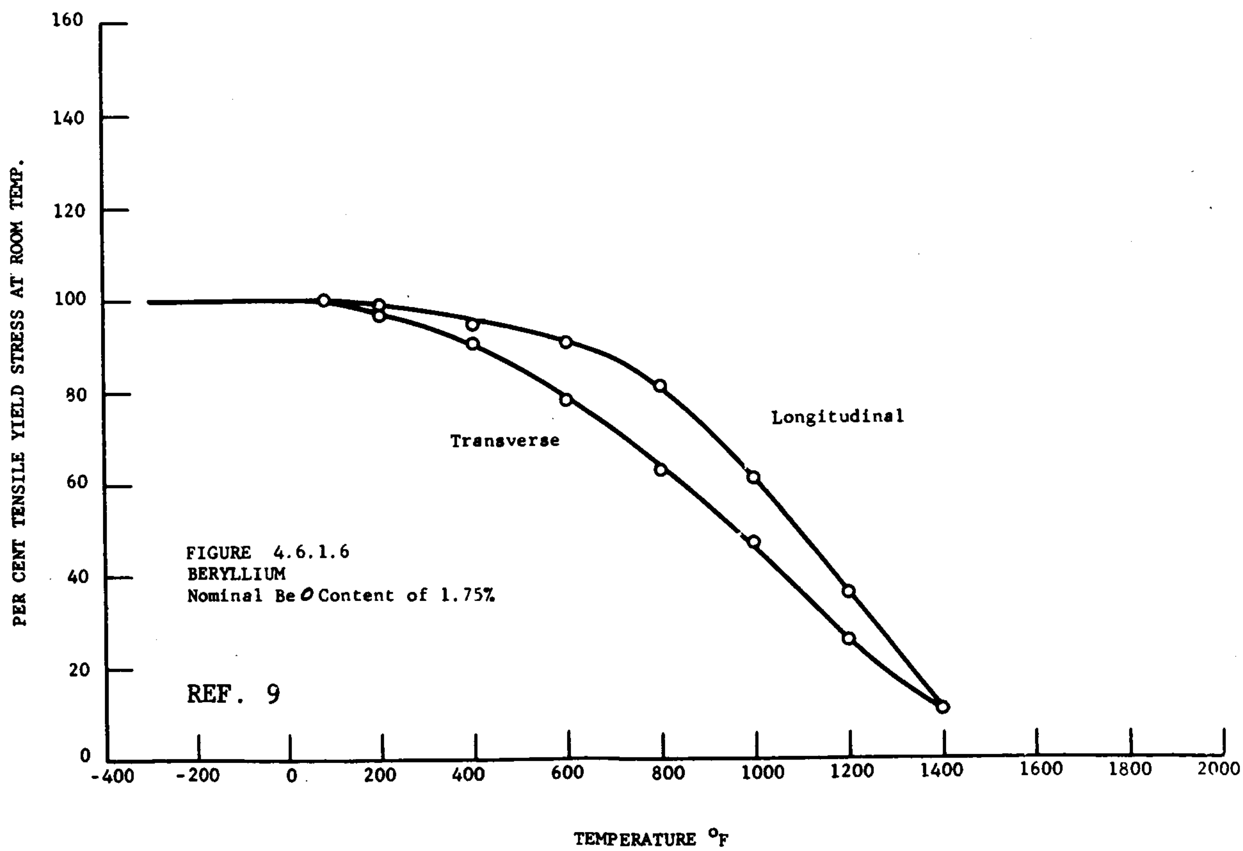

Figure 6 Yield Stress as a Function of Temperature - Beryllium

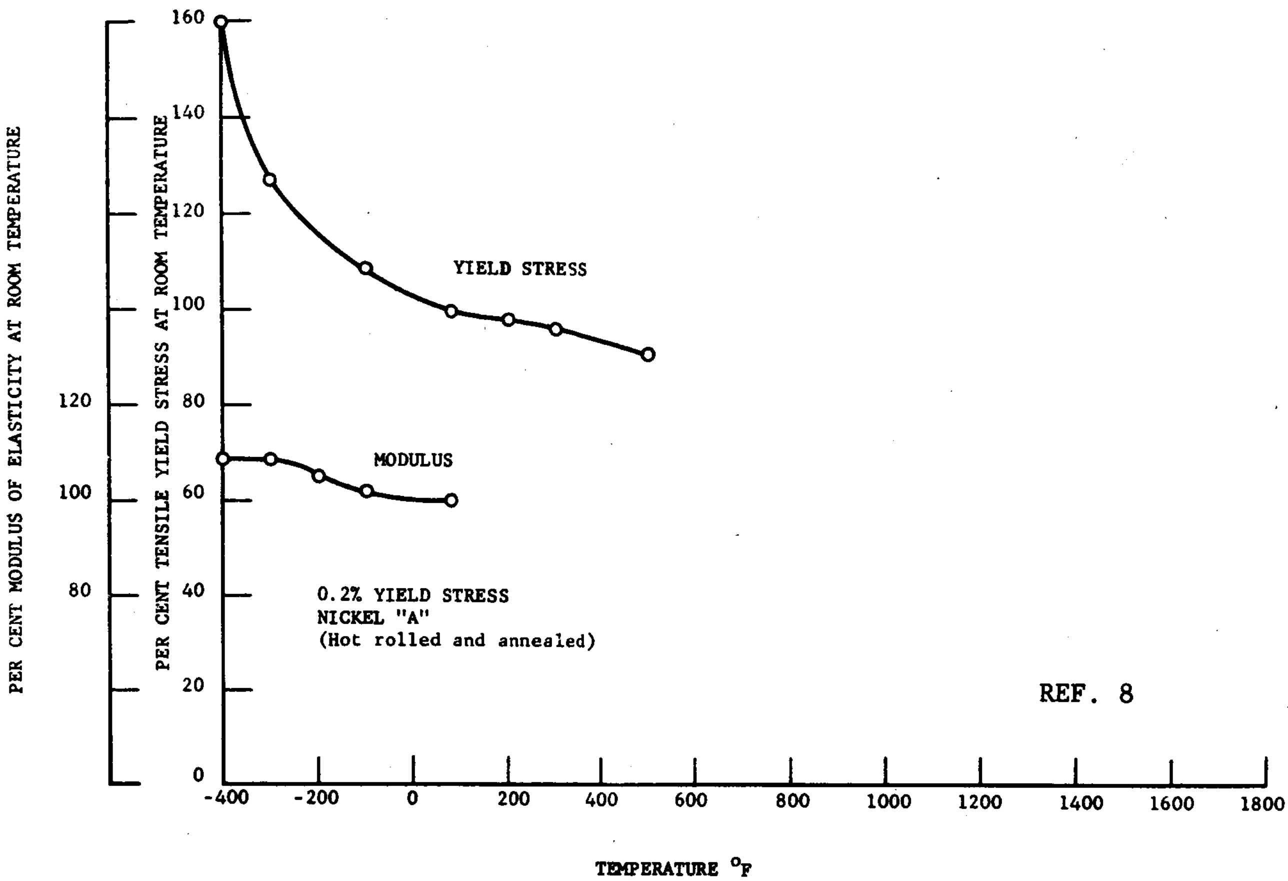

Figure 13. Yield Stress as a Function of Temperature - Nickel "A"

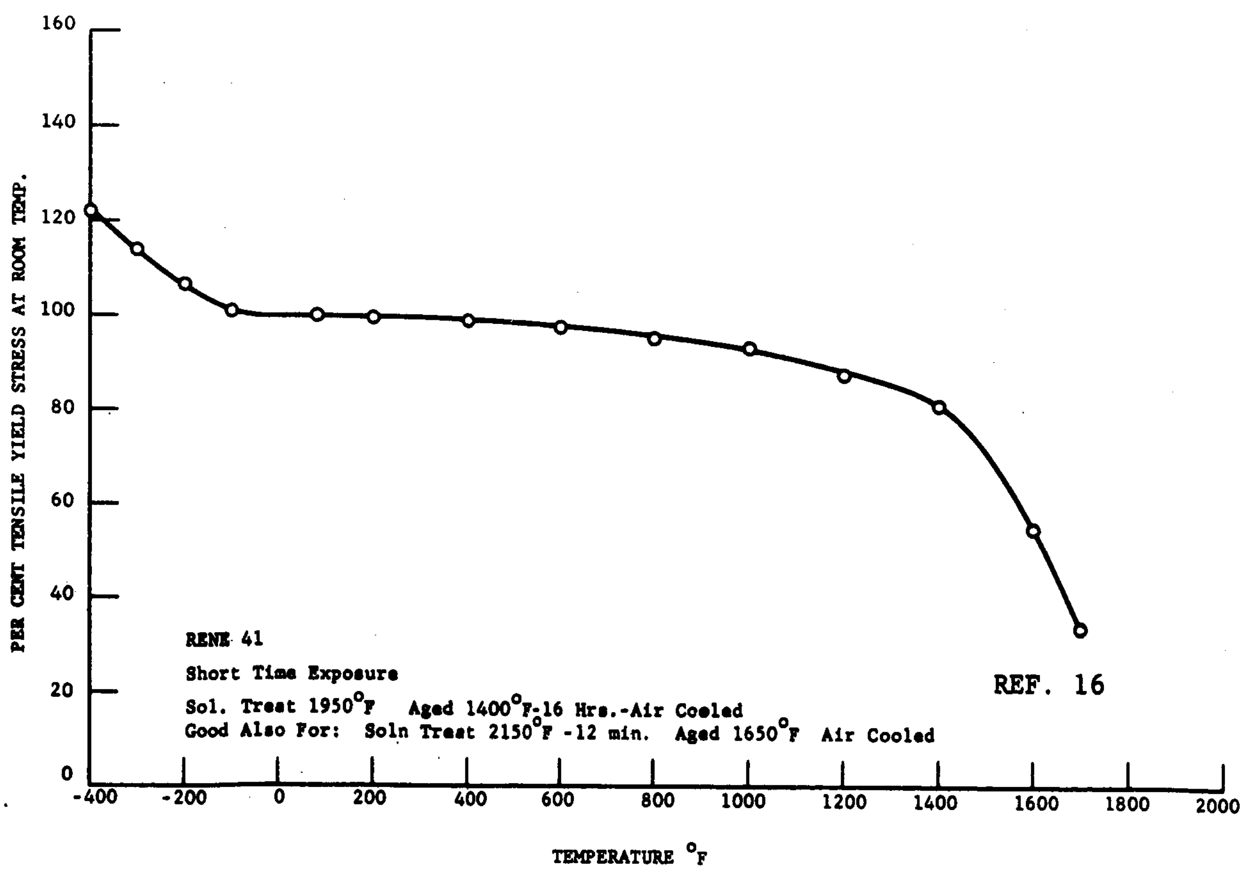

Figure 14 Yield Stress as a Function of Temperature - Rene 41

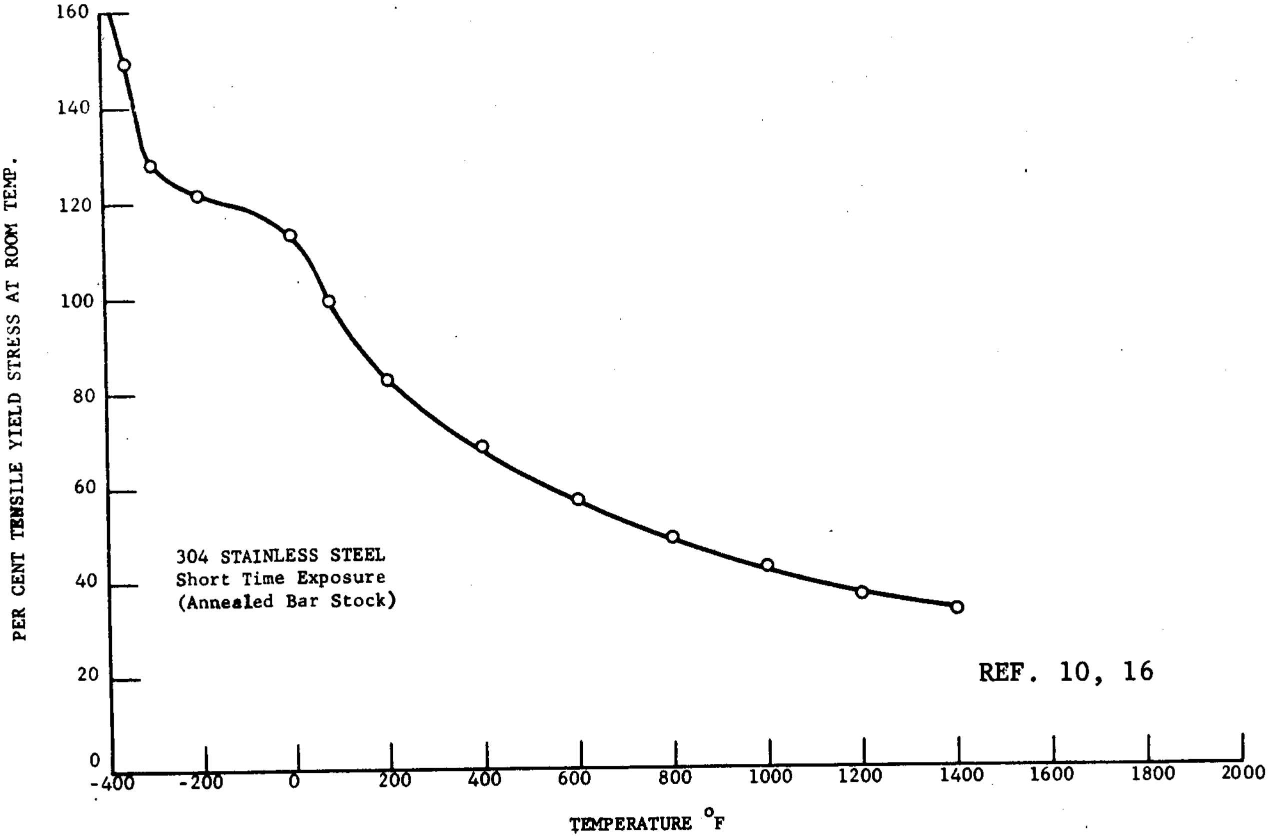

Figure 15 Yield Stress as a Function of Temperature - Stainless Steel 304

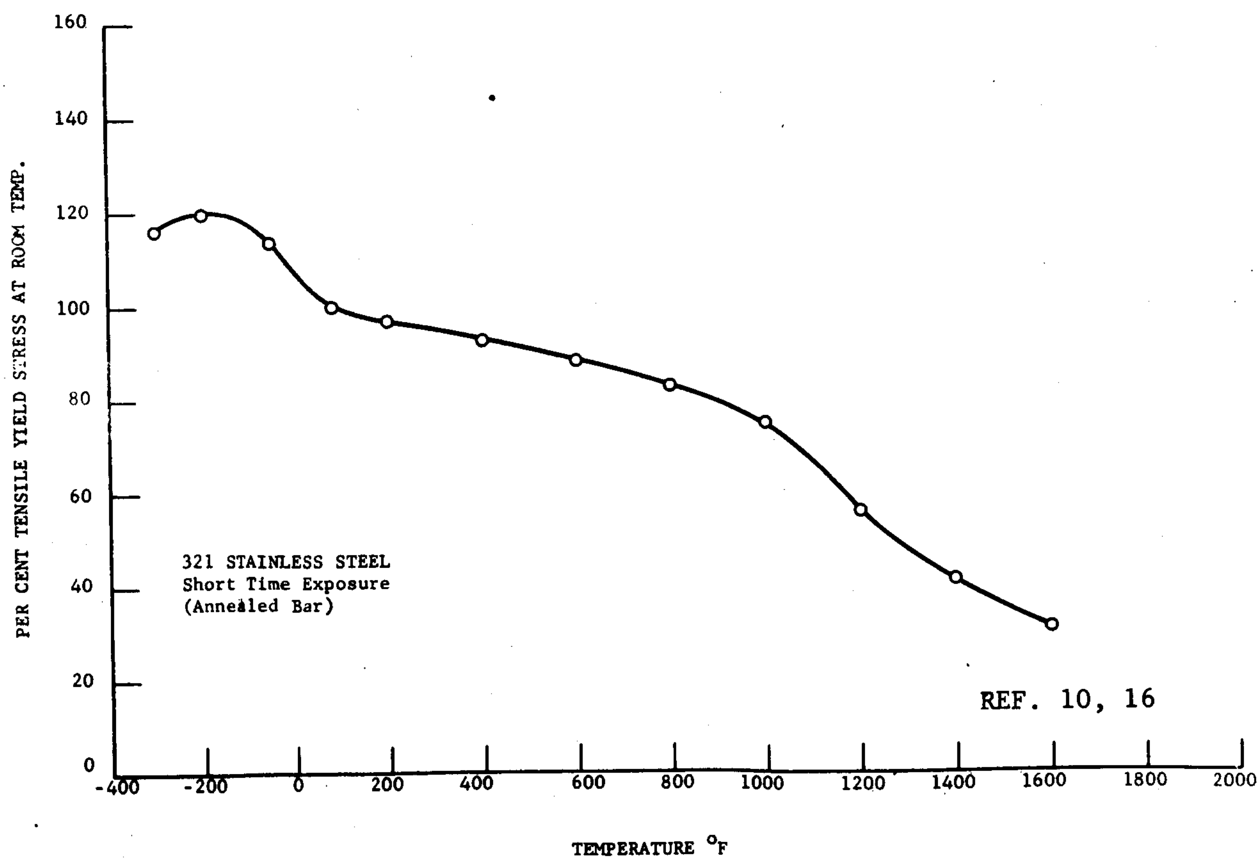

Figure 16 Yield Stress as a Function of Temperature - Stainless Steel 321

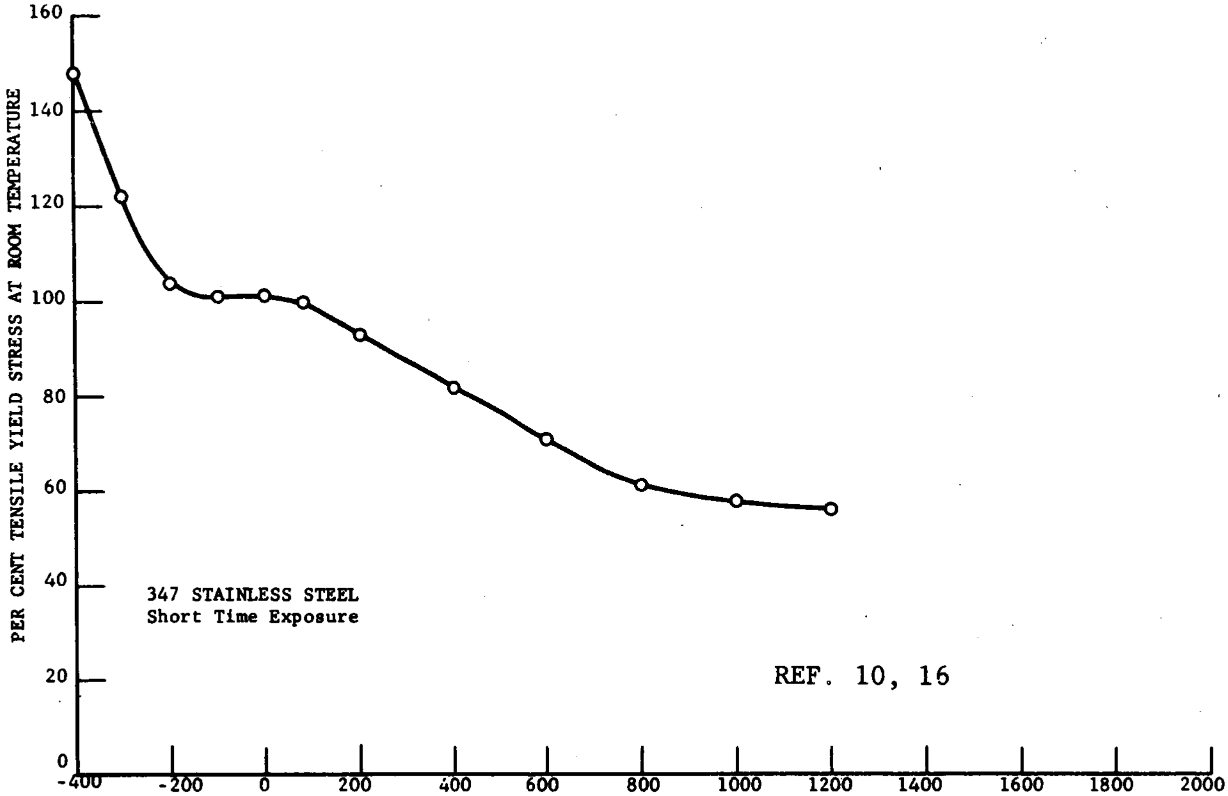

Figure 17 Yield Stress as a Function of Temperature - Stainless Steel 347

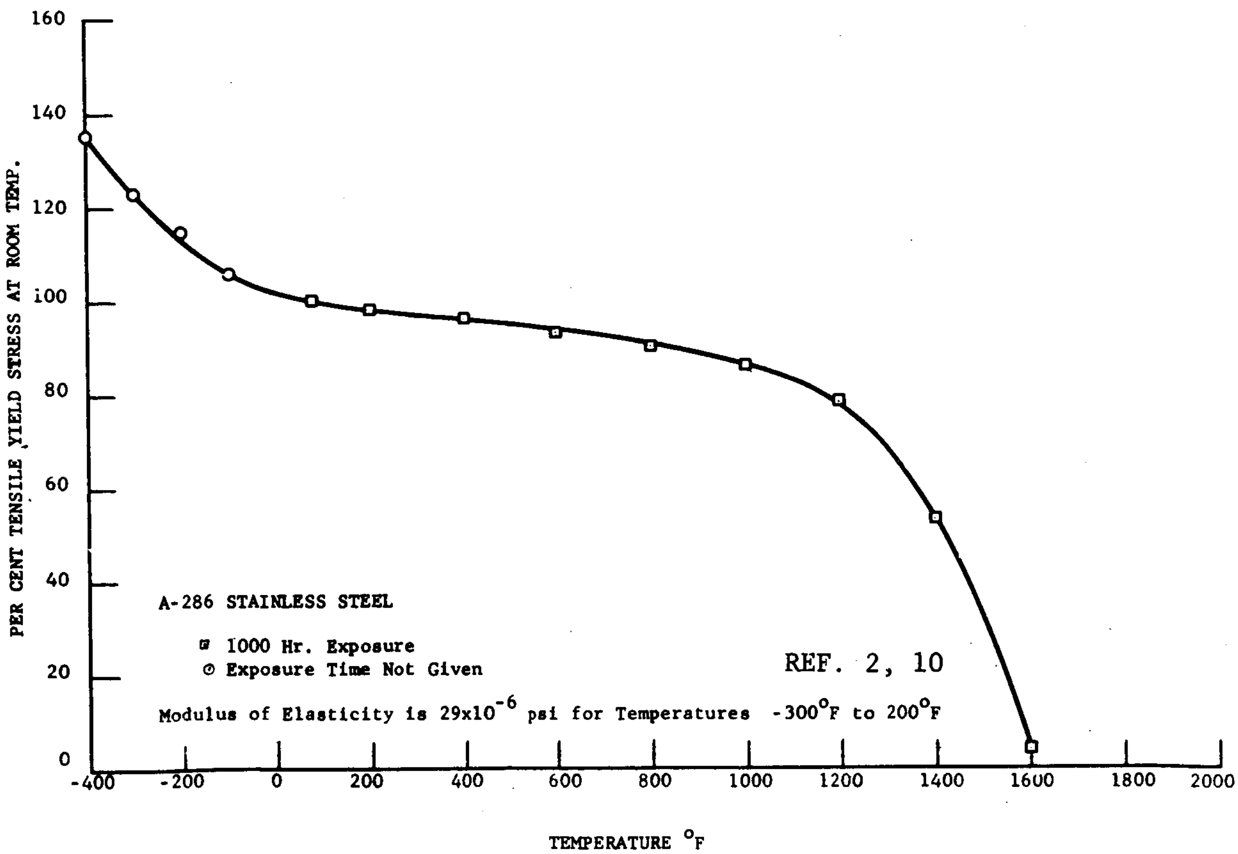

Figure 18 Yield Stress as a Function of Temperature - Stainless Steel A-286

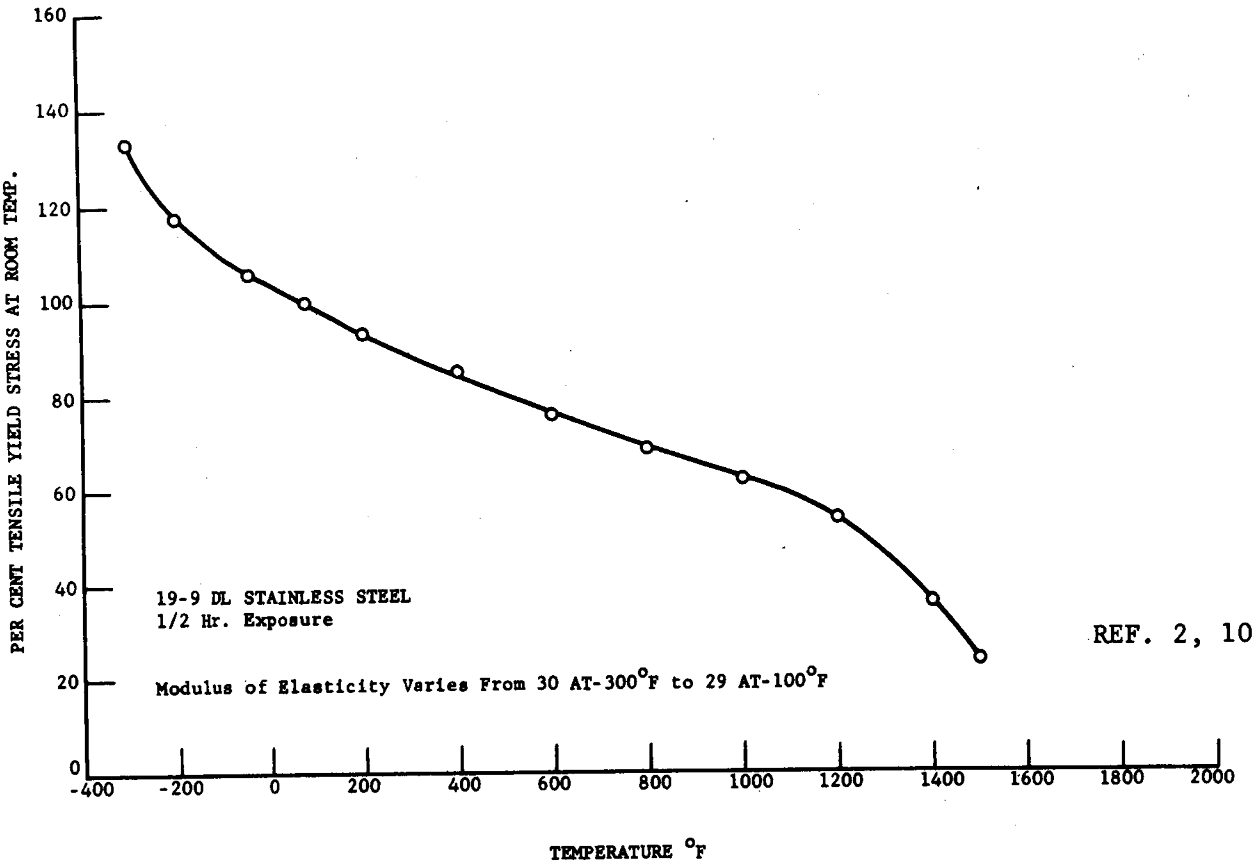

Figure 19 Yield Stress as a Function of Temperature - Stainless Steel 19-9 DL

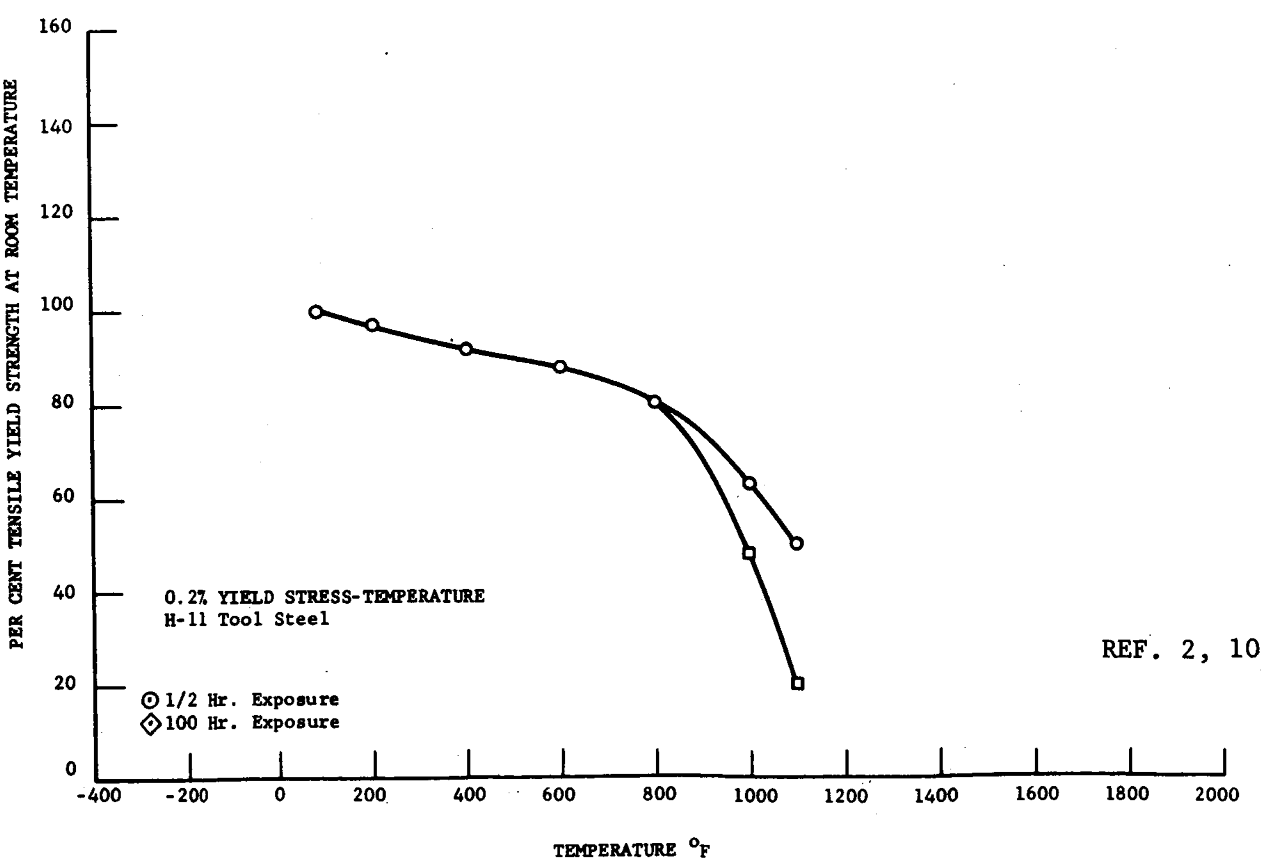

Figure 20 Yield Stress as a Function of Temperature - Tool Steel H-11

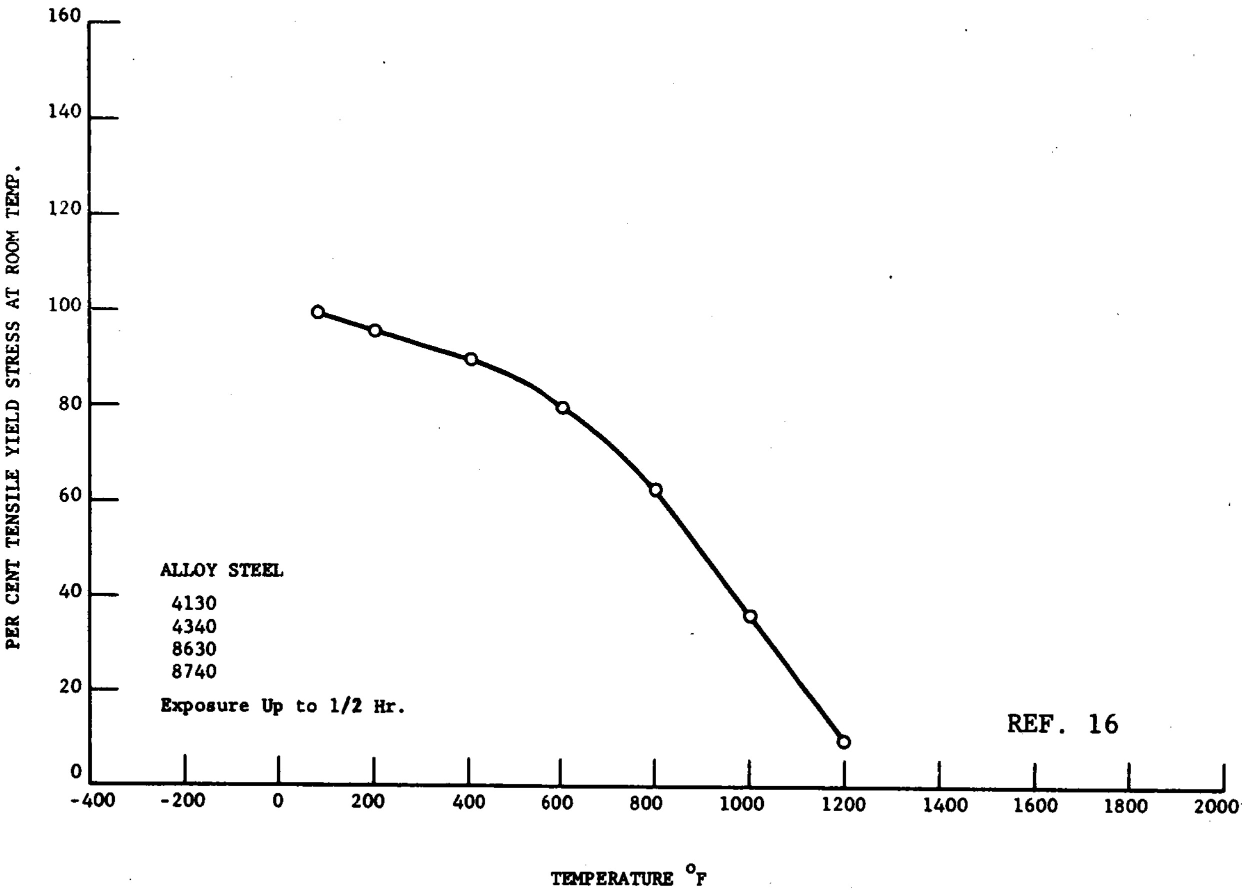

Figure 21 Yield Stress as a Function of Temperature - Alloy Steel 4130, 4340, 8630, 8740

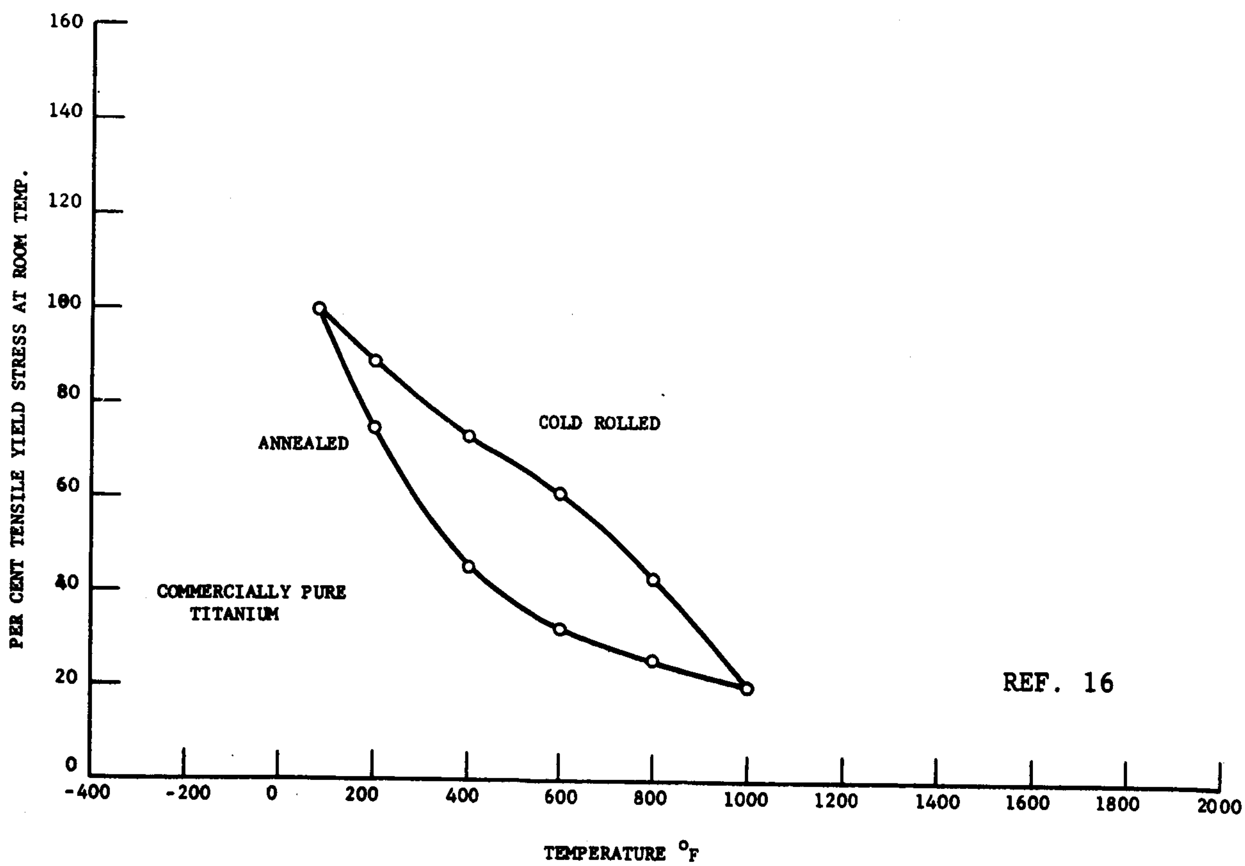

Figure 22 Yield Stress as a Function of Temperature - Commercially Pure Titanium

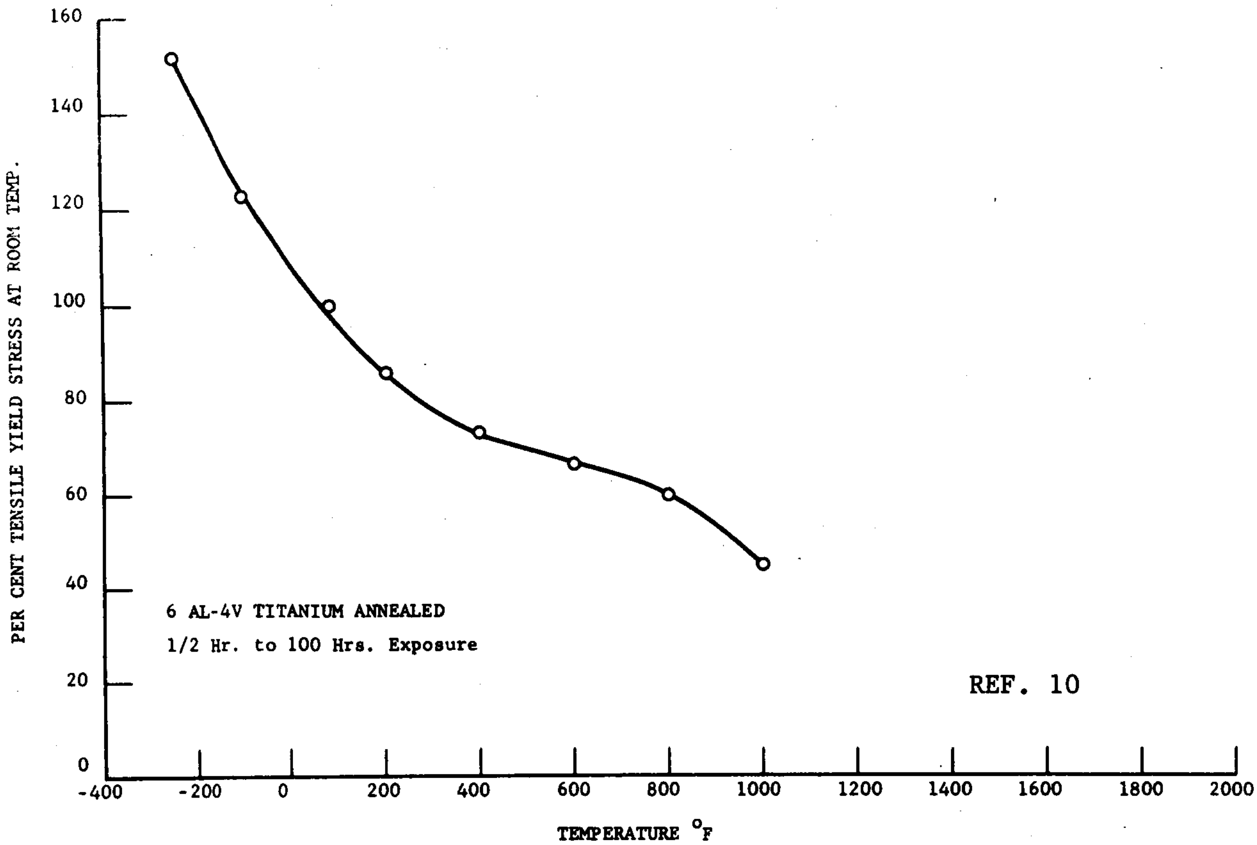

Figure 23 Yield Stress as a Function of Temperature - Titanium Annealed 6 AL-4V

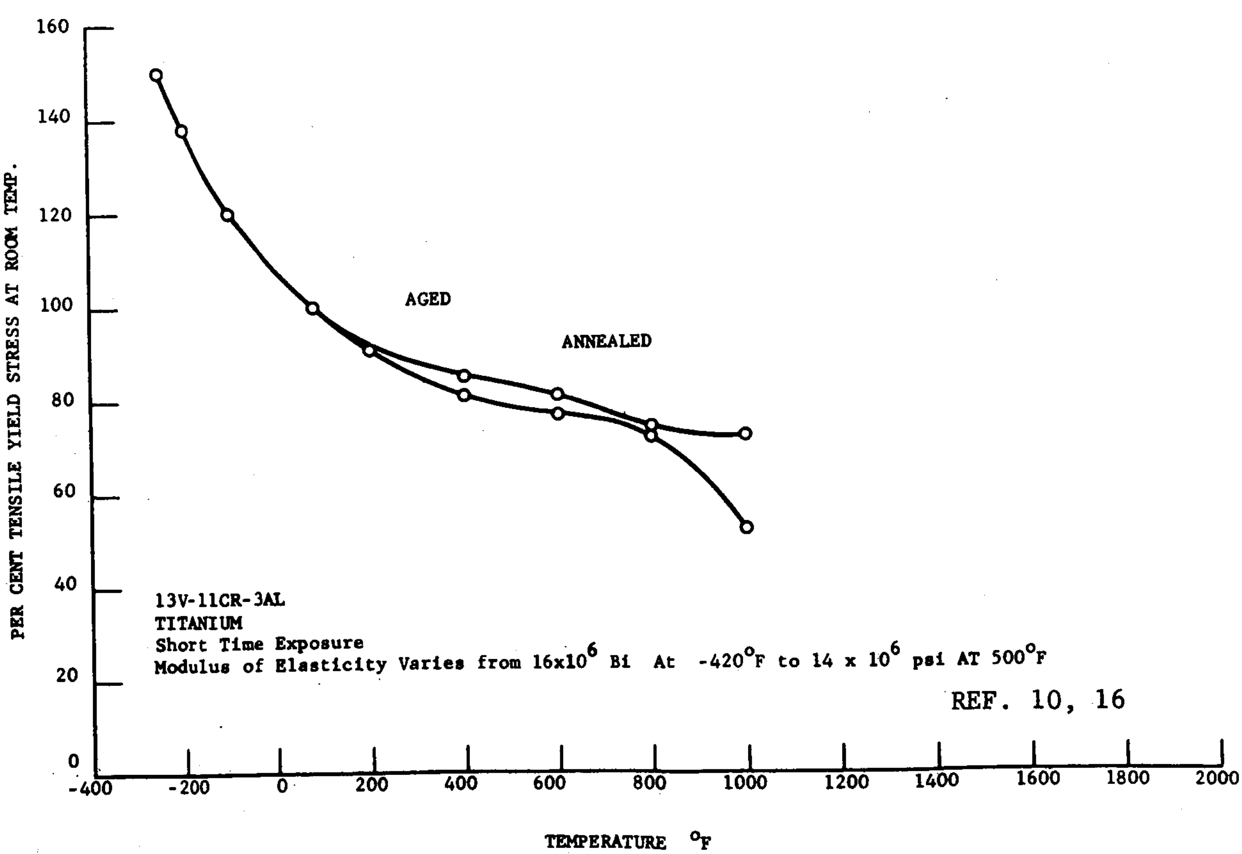

Figure 24 Yield Stress as a Function of Temperature - Titanium 13V-11CR-3AL

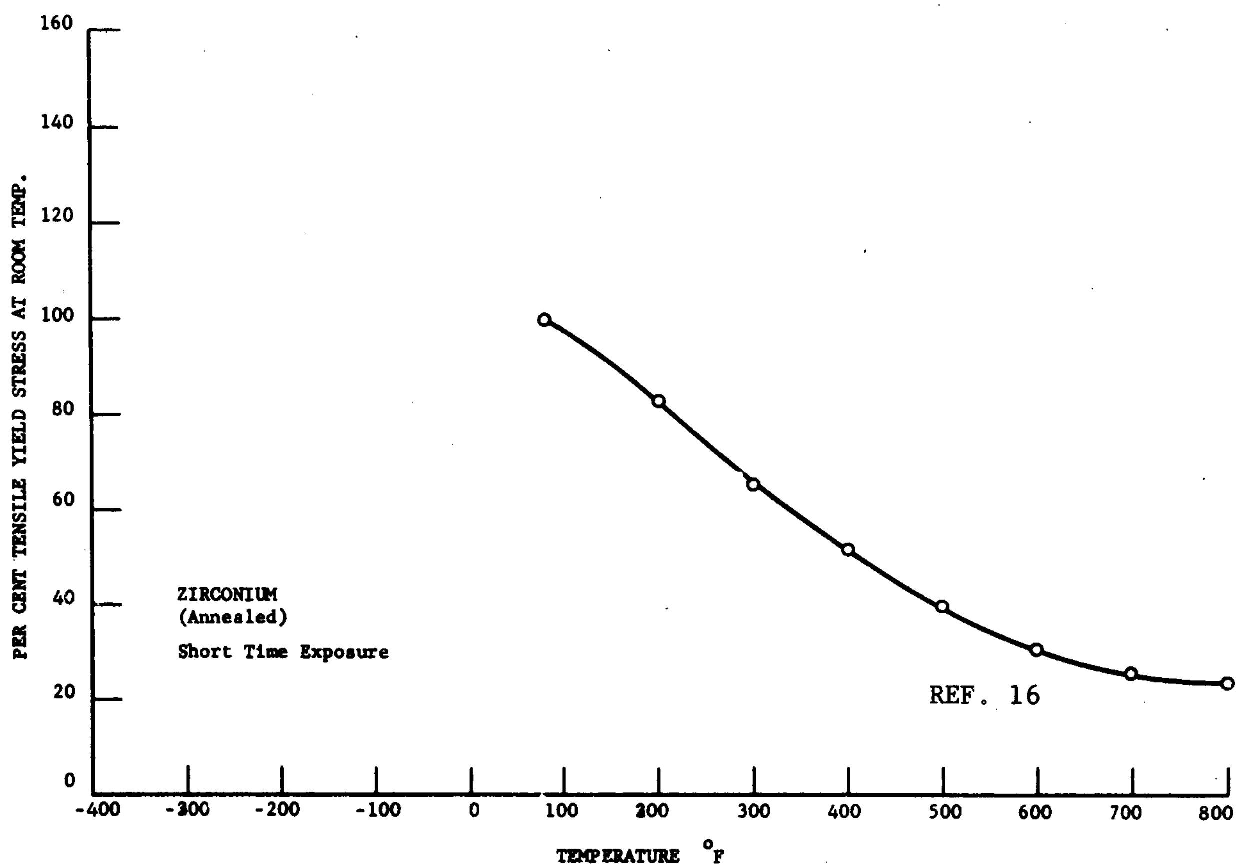

Figure 25 Yield Stress as a Function of Temperature - Zirconium

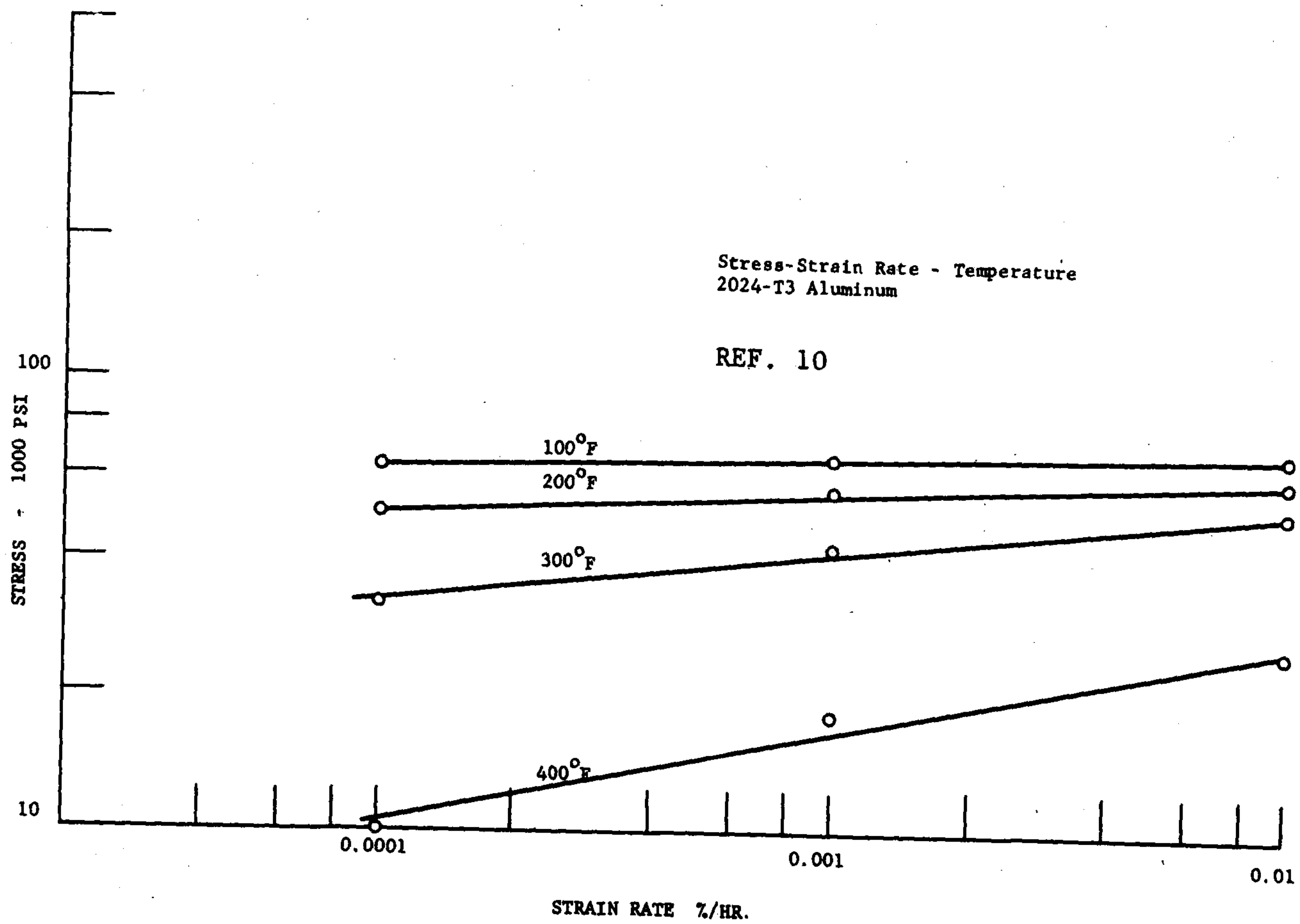

Figure 26 Creep Data - Aluminum 2024-T3

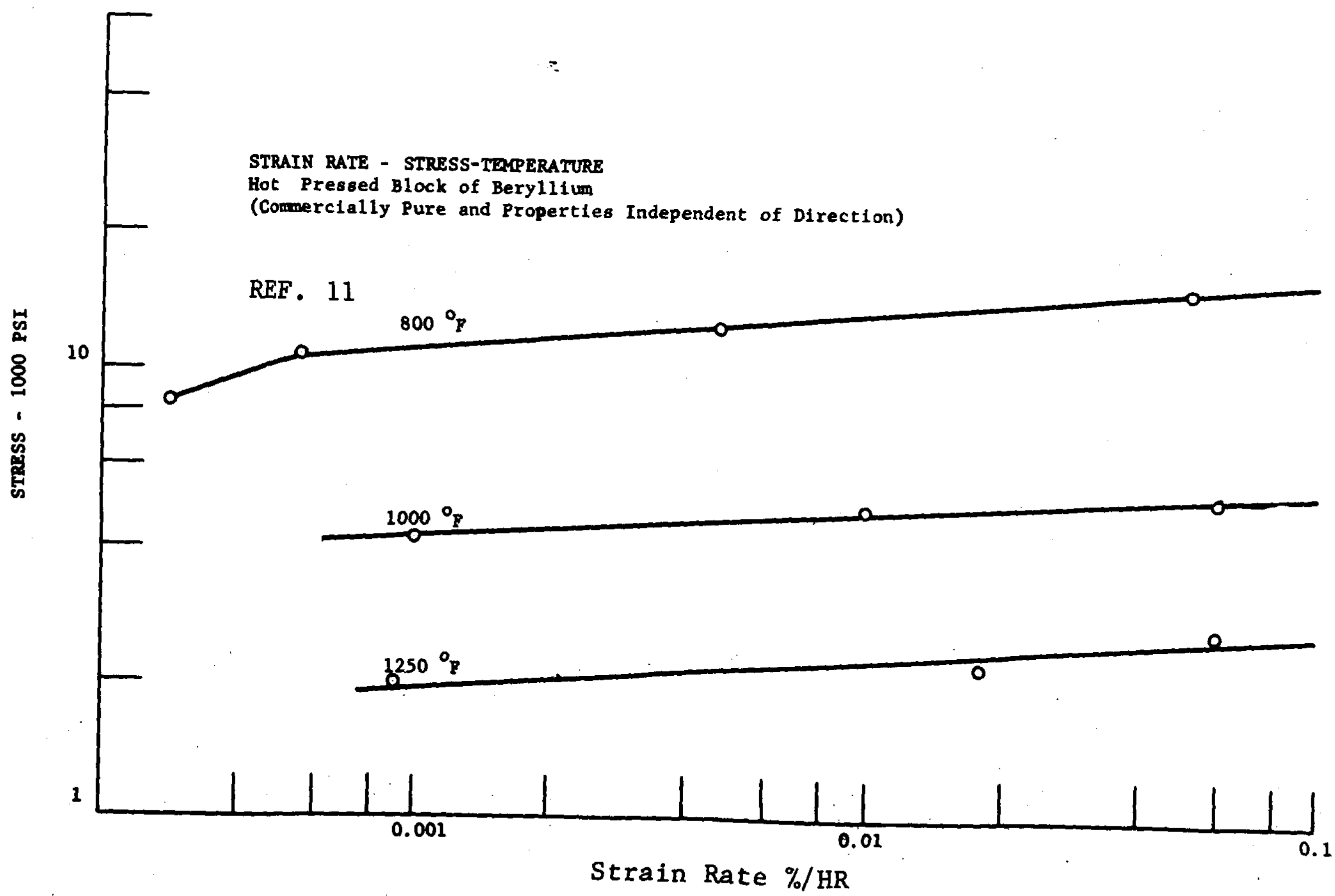

Figure 27 Creep Data - Beryllium

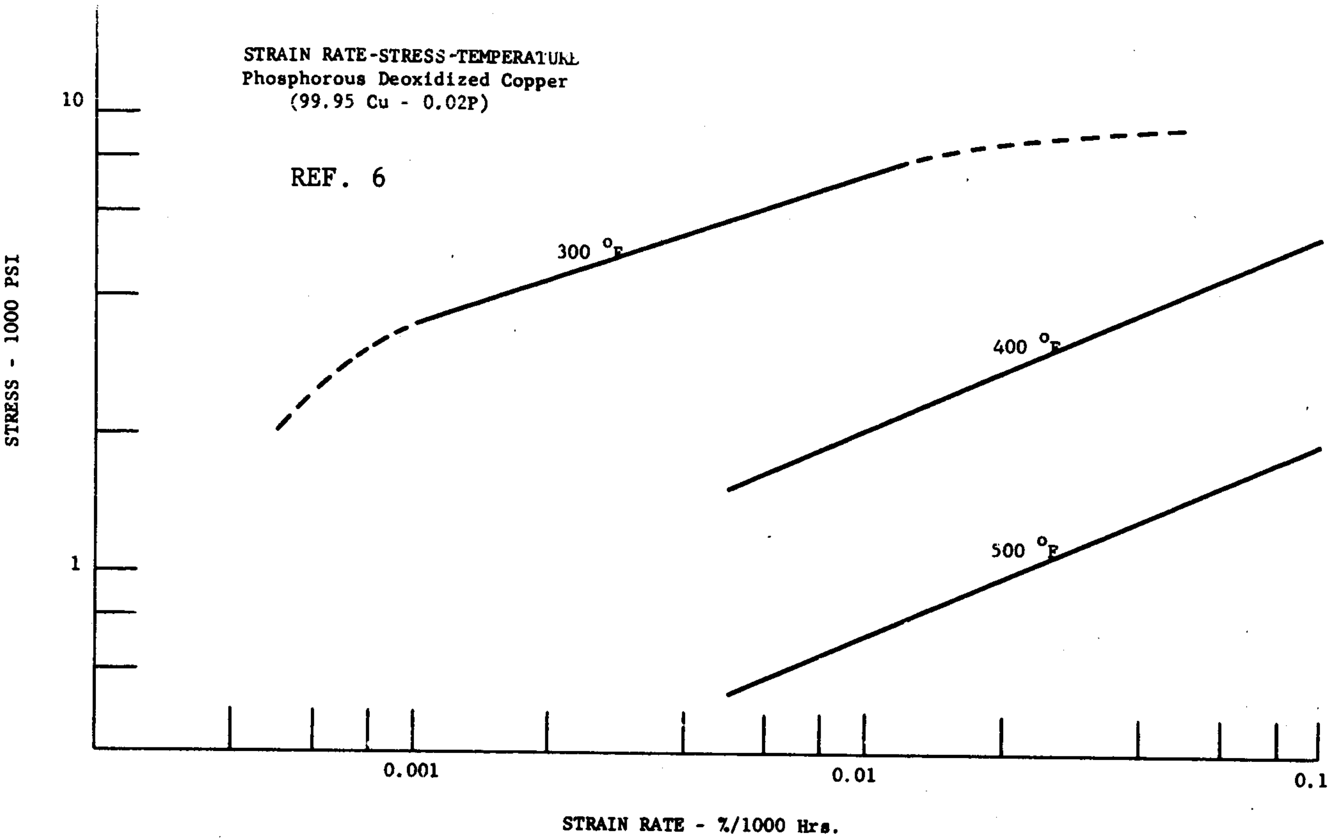

Figure 28 Creep Data - Phosphorous Deoxidized Copper

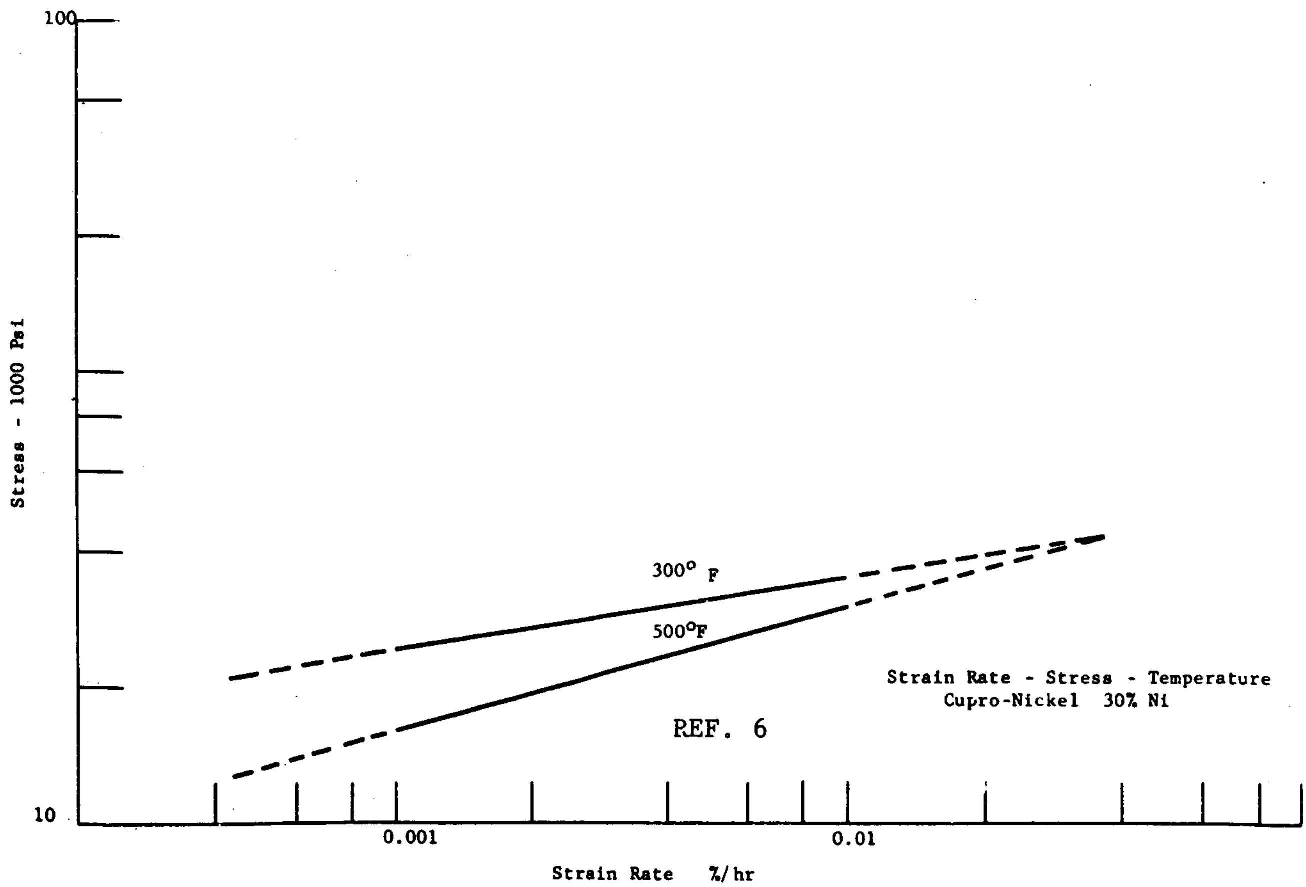

Figure 29 Creep Data - Cupro-Nickel 30% Ni

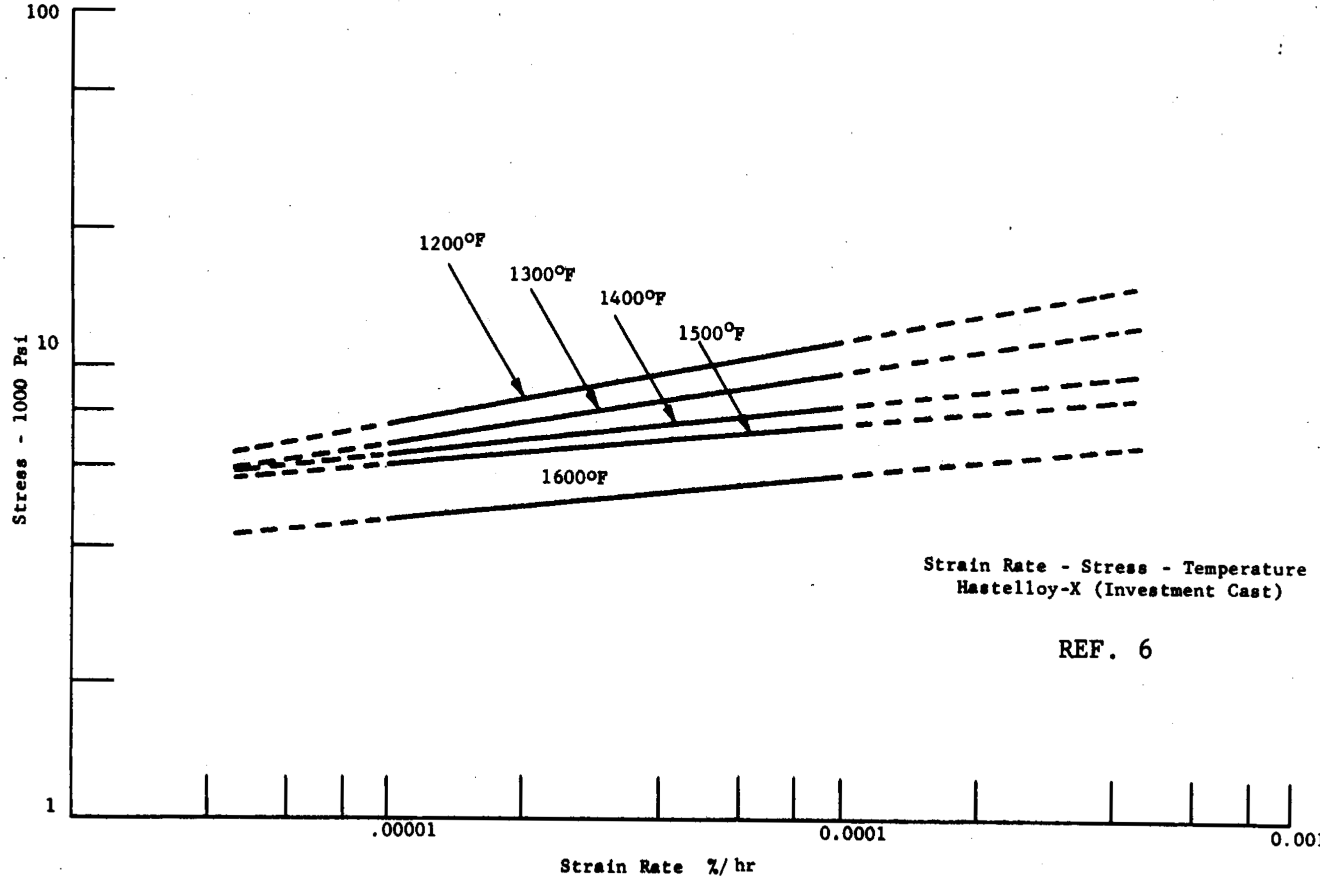

Figure 30 Creep Data - Hastelloy-X

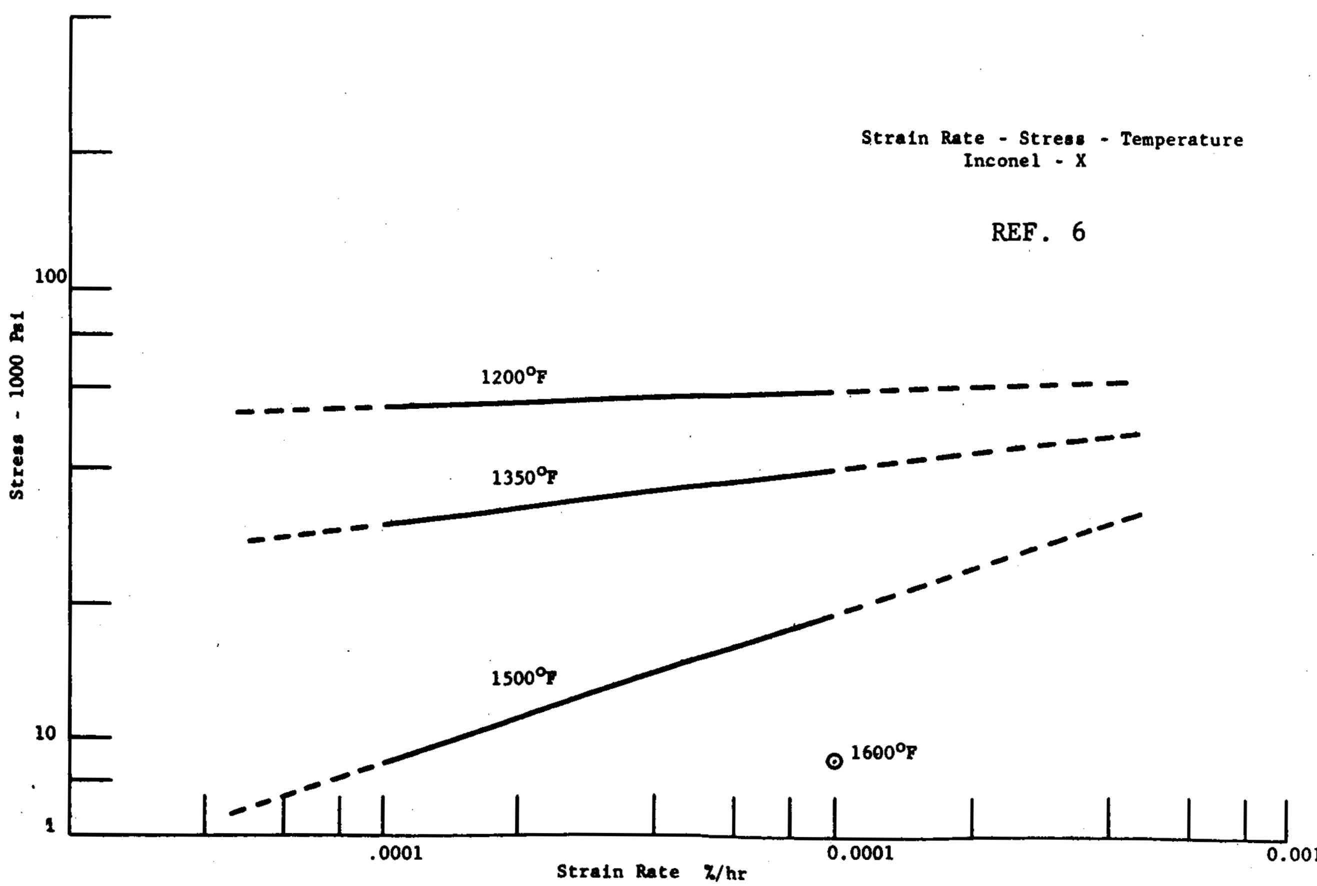

Figure 31 Creep Data - Inconel-X

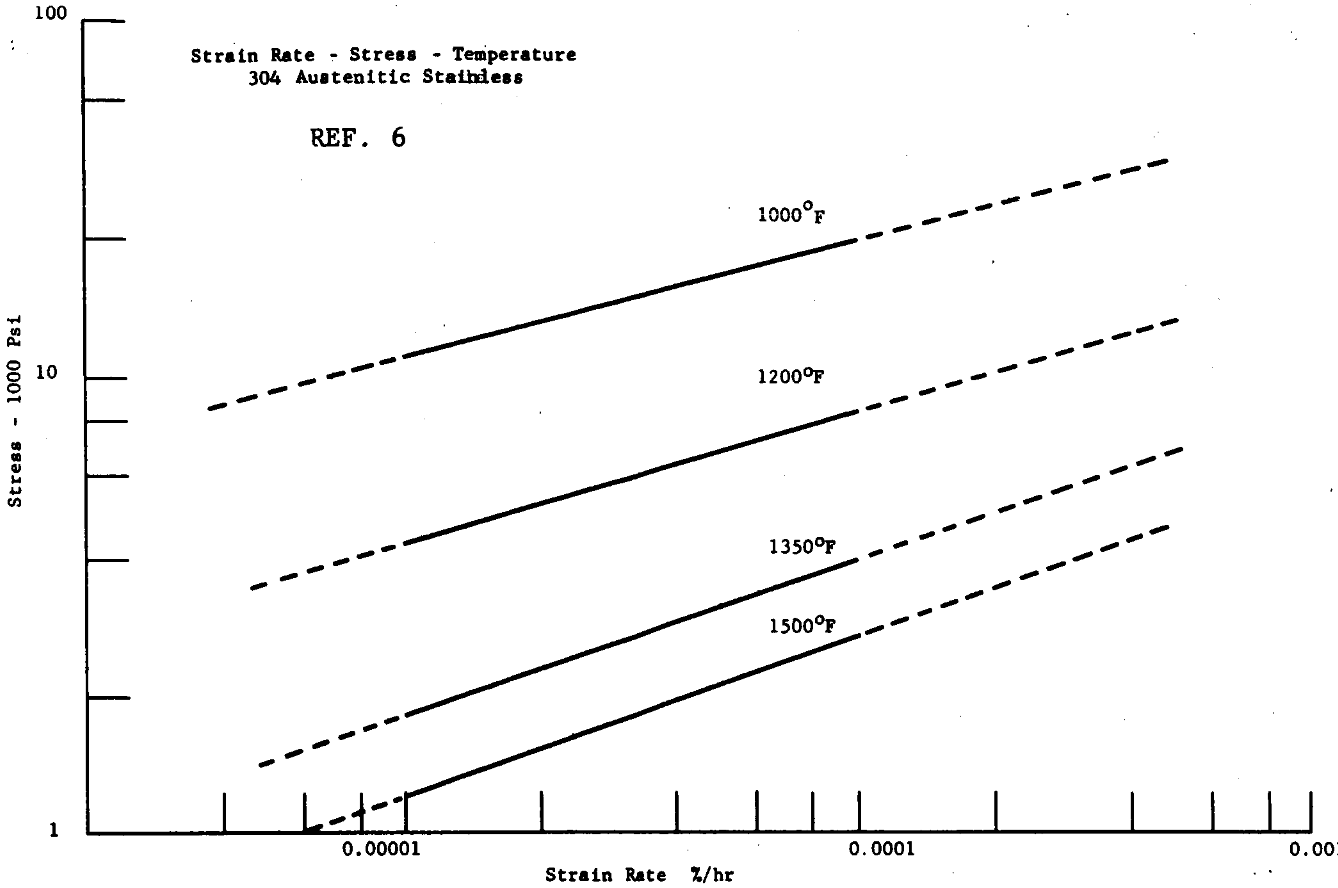

Figure 32 Creep Data - Austenitic Stainless 304

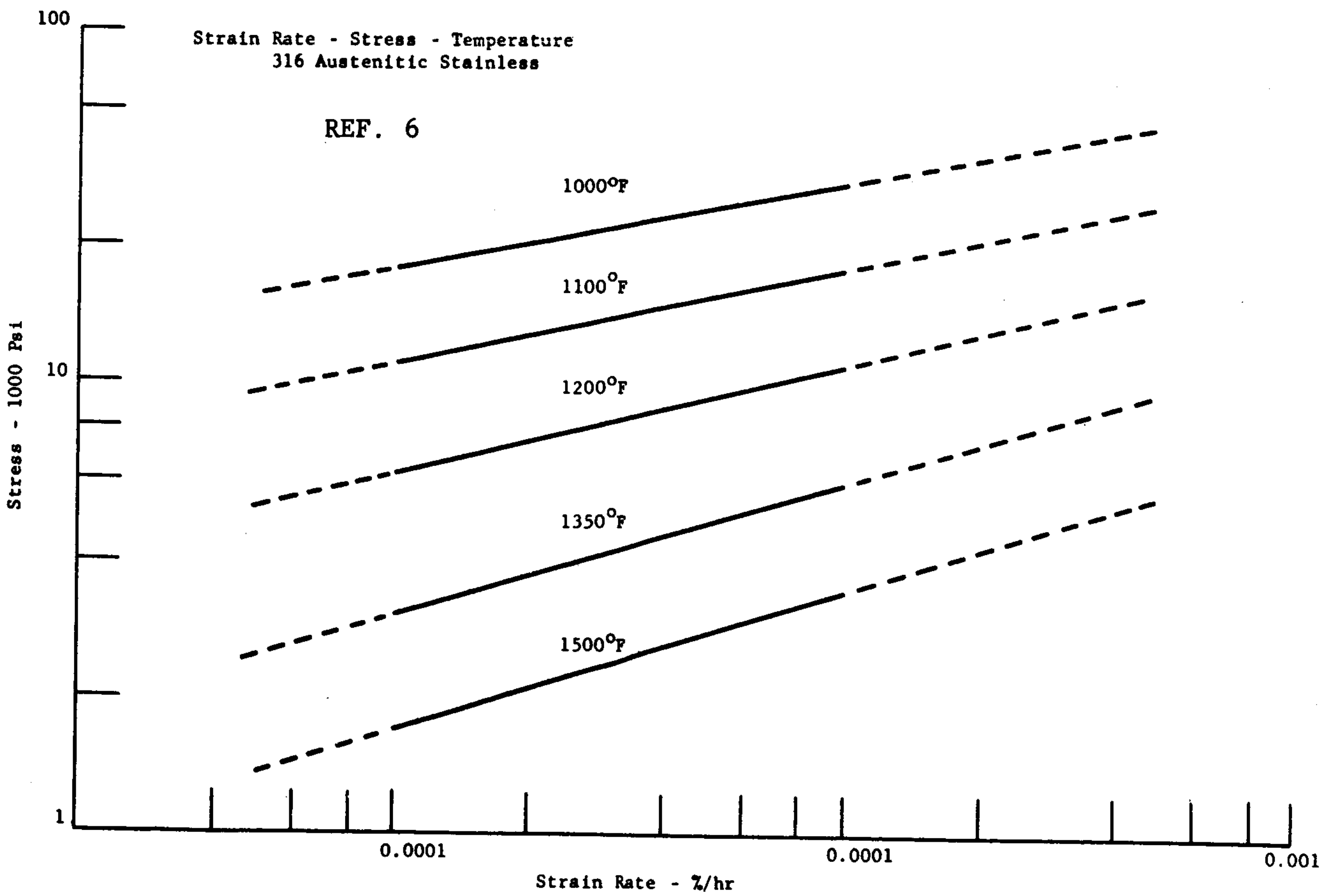

Figure 33 Creep Data - Austenitic Stainless 316

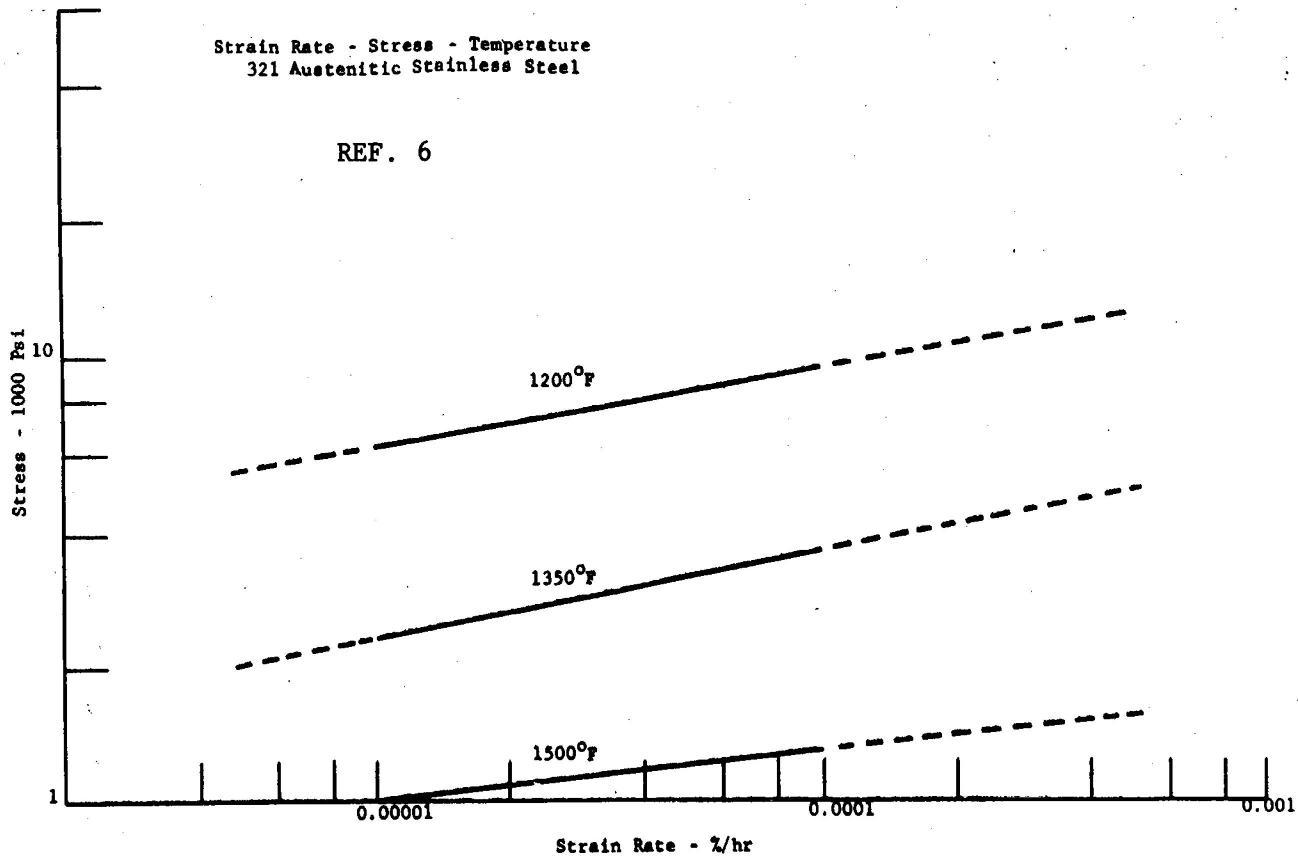

Figure 34 Creep Data - Austenitic Stainless Steel 321

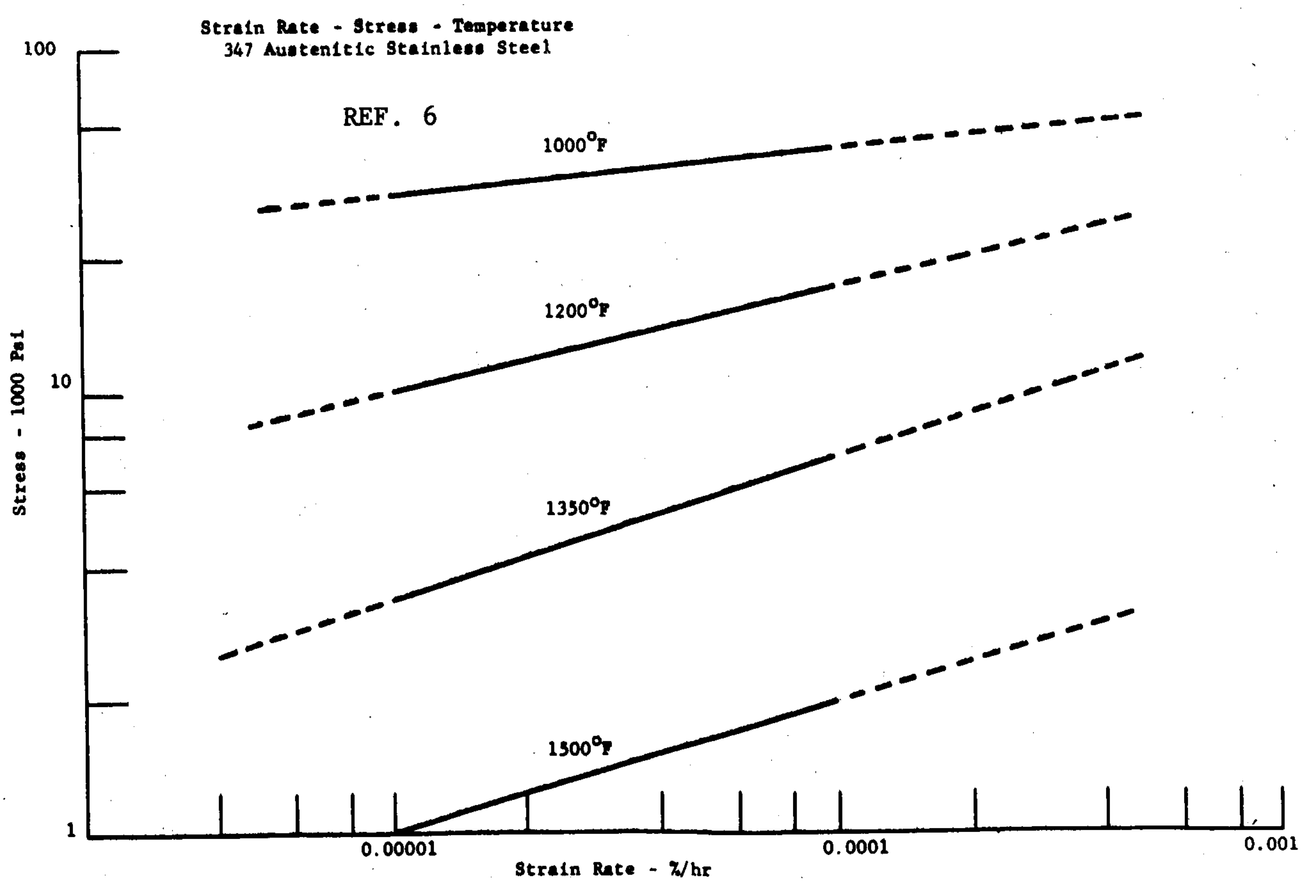

Figure 35 Creep Data - Austenitic Stainless Steel 347

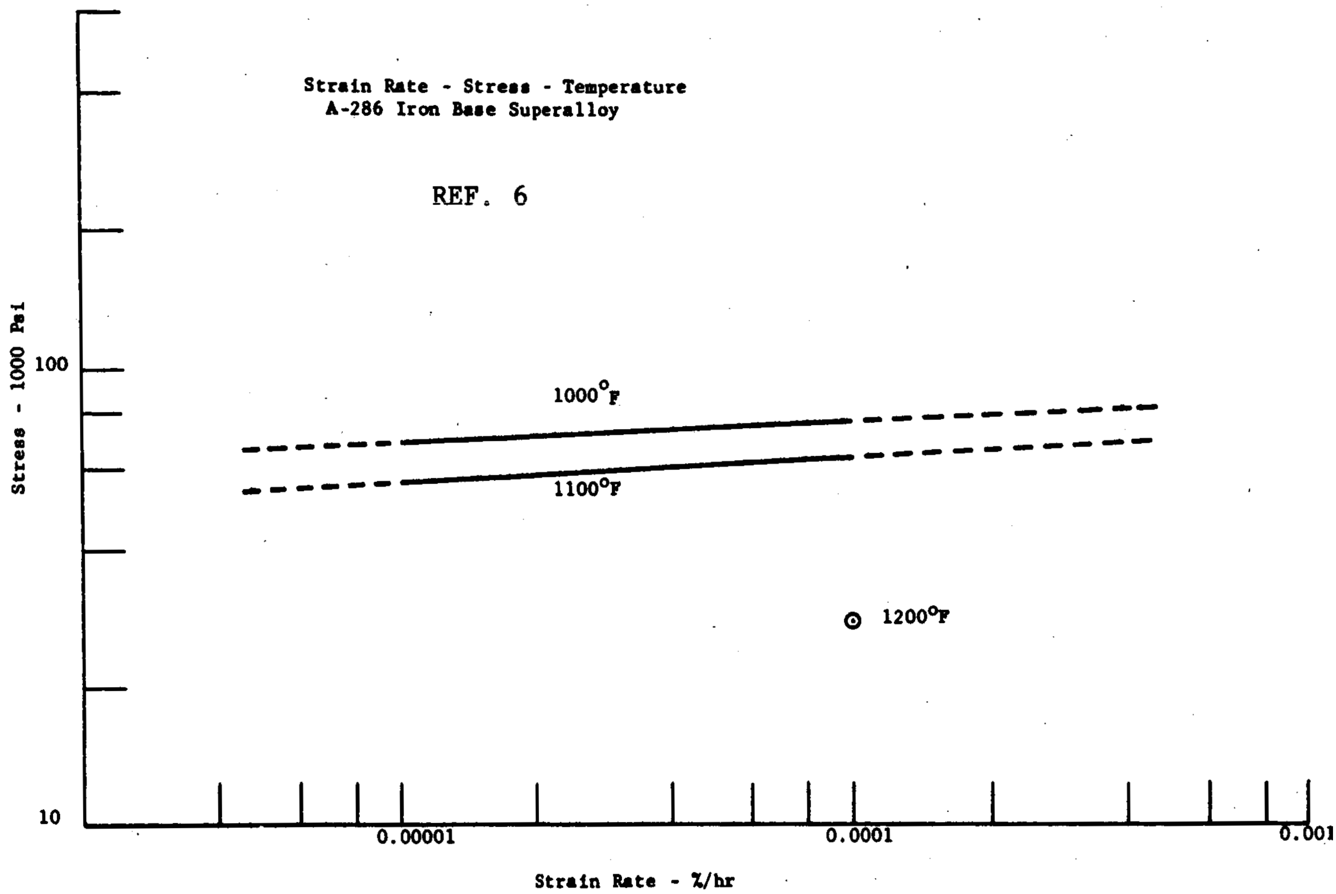

Figure 36 Creep Data - Iron Base Superalloy A-286

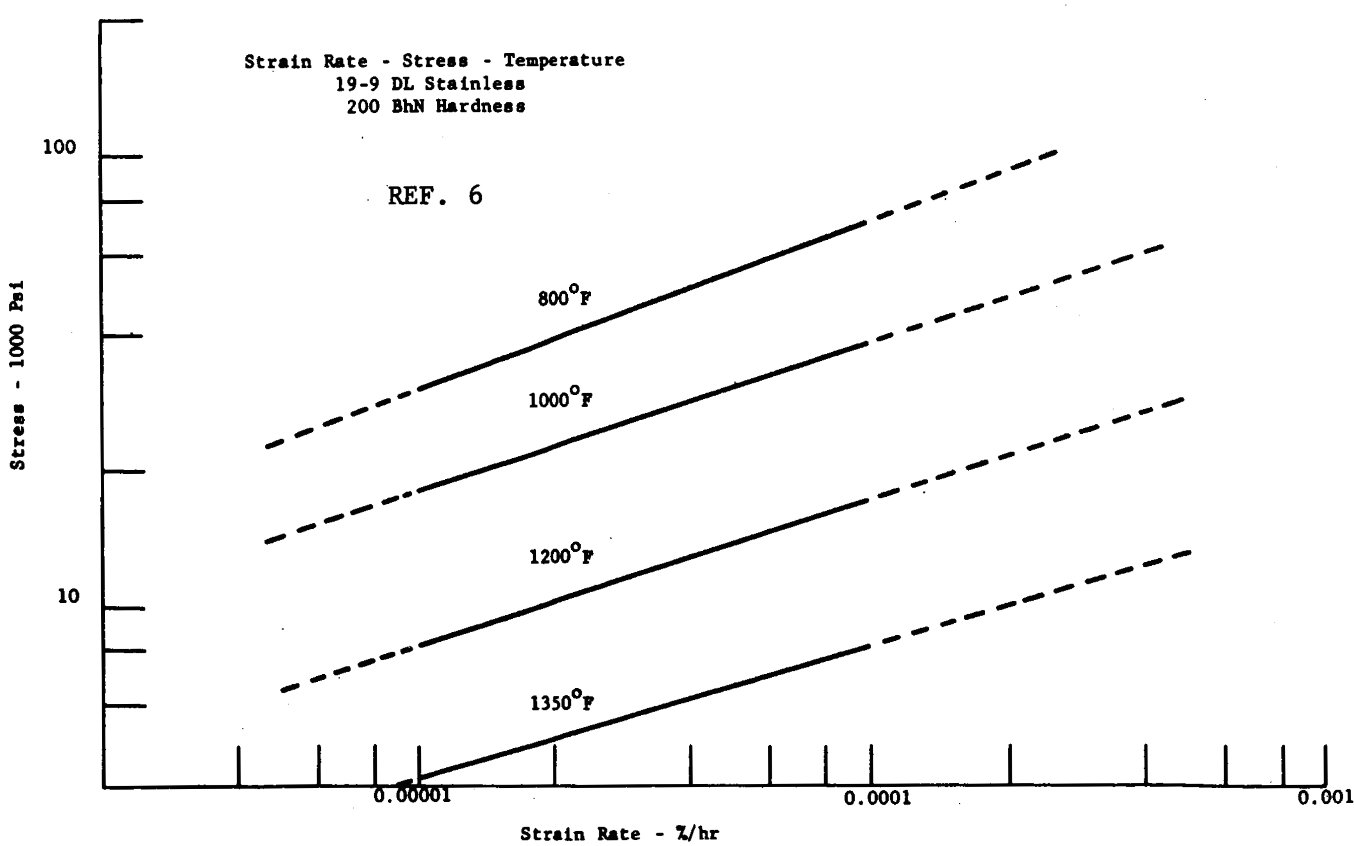

Figure 37 Creep Data - DL Stainless 19-9

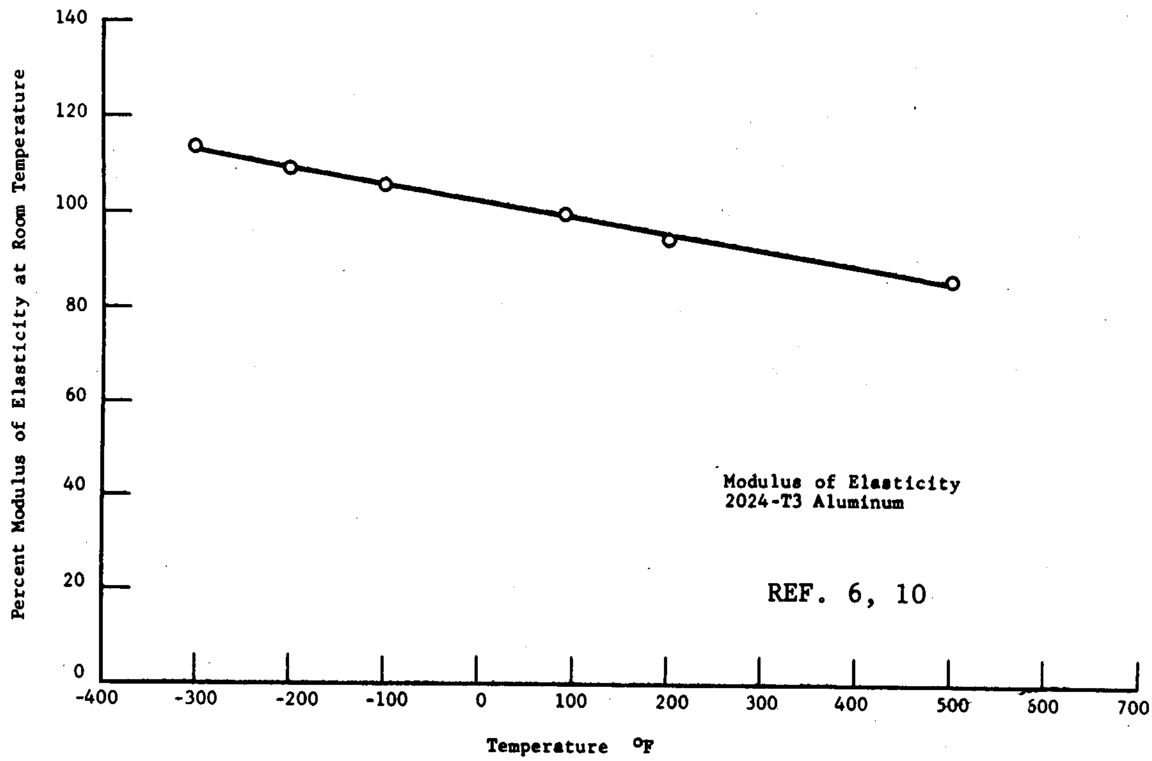

Figure 38 Modulus of Elasticity as a Function of Temperature - Aluminum 2024-T3

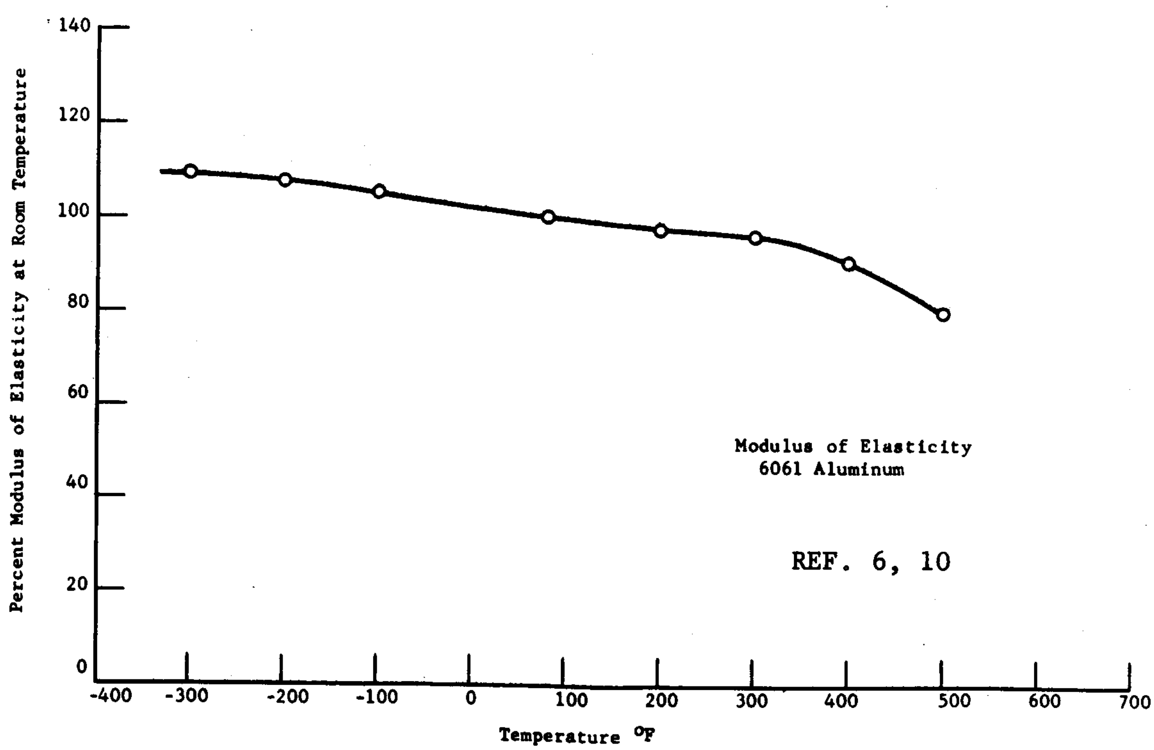

Figure 39 Modulus of Elasticity as a Function of Temperature - Aluminum 6061

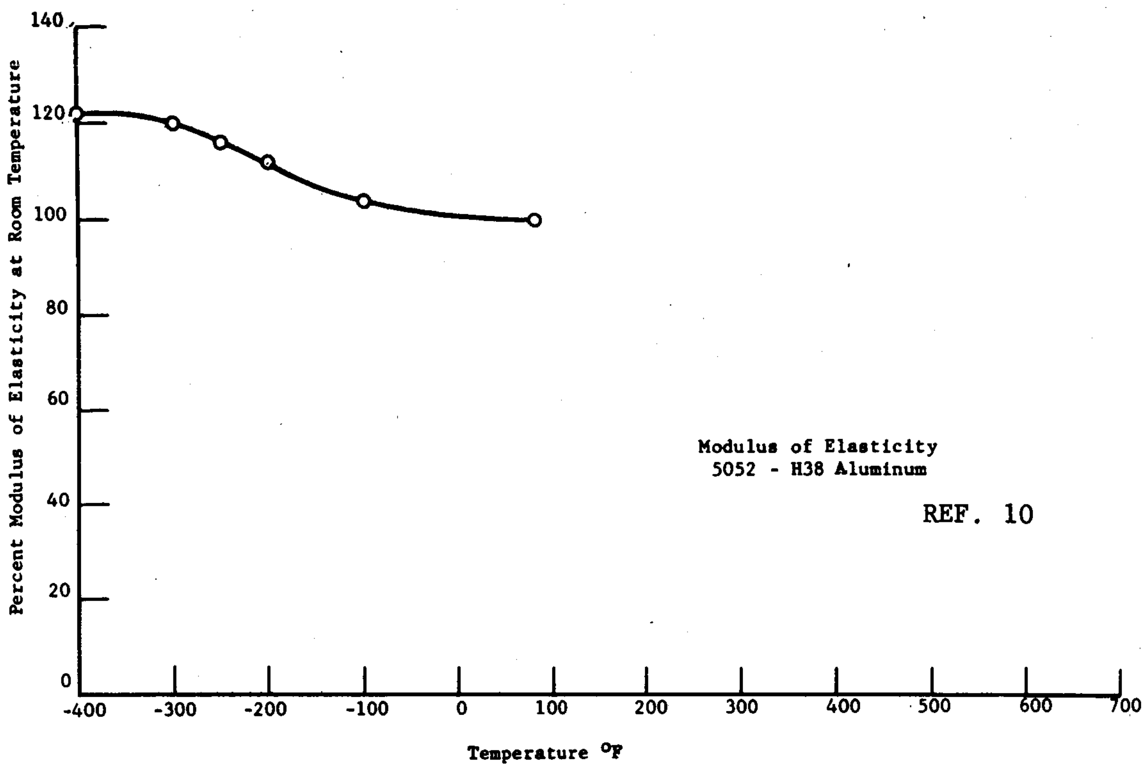

Figure 40 Modulus of Elasticity as a Function of Temperature - H38 Aluminum 5052

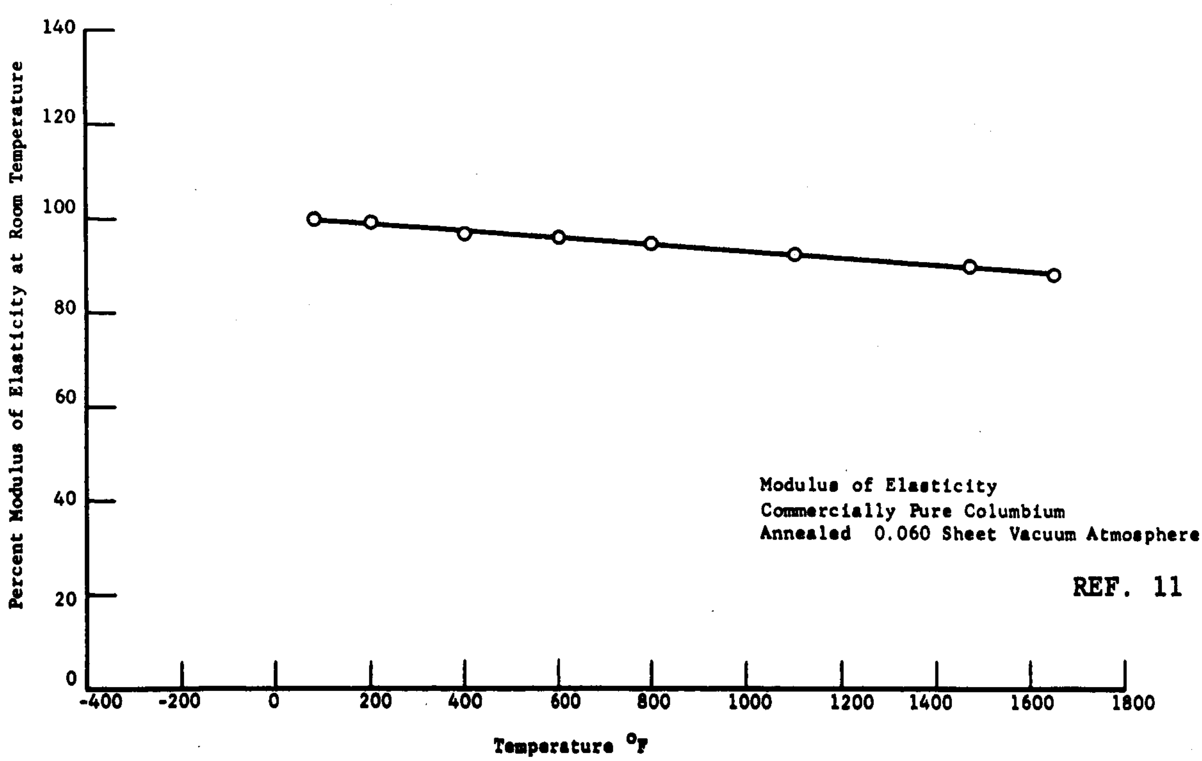

Figure 41 Modulus of Elasticity as a Function of Temperature- Columbium

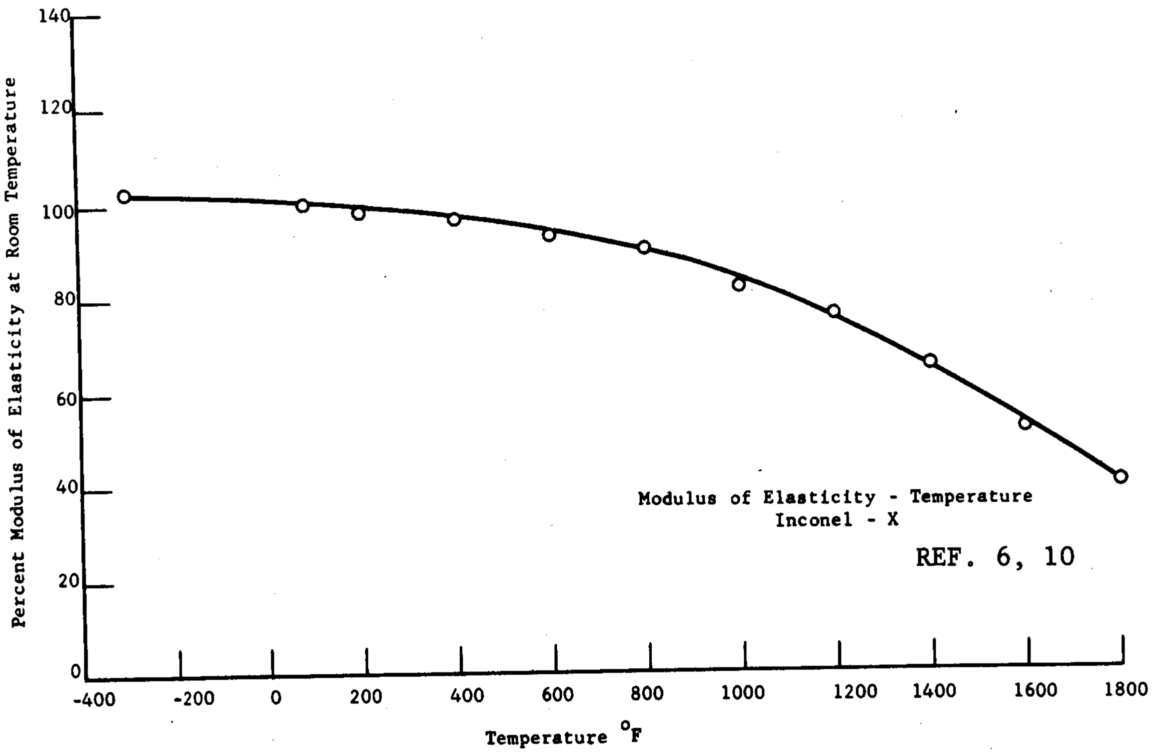

Figure 42 Modulus of Elasticity as a Function of Temperature - Inconel-X

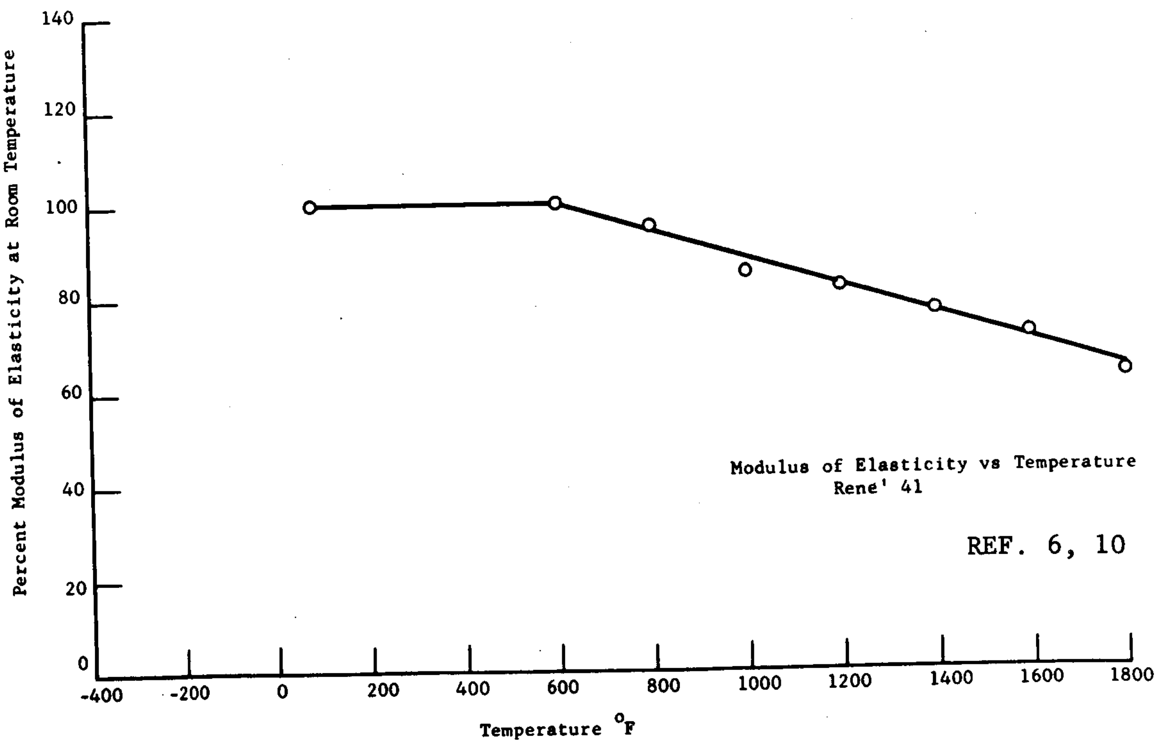

Figure 43 Modulus of Elasticity as a Function of Temperature - Rene ' 41

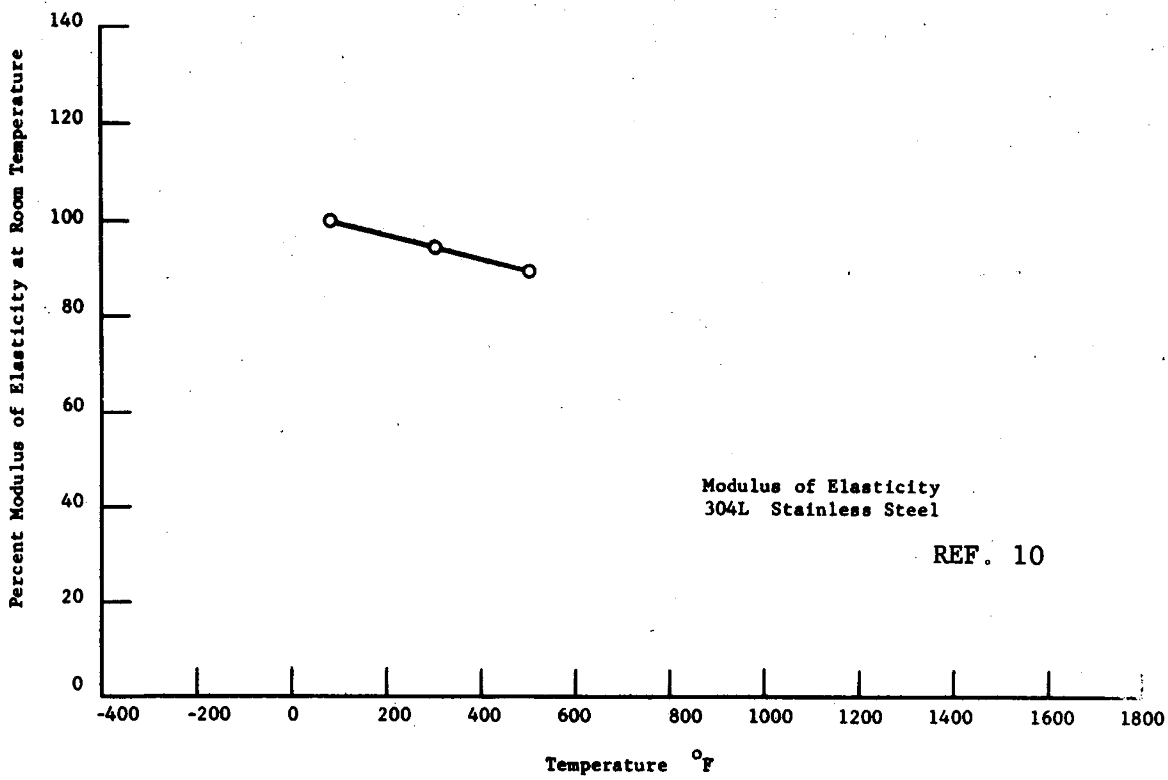

Figure 44 Modulus of Elasticity as a Function of Temperature - Stainless Steel 304L

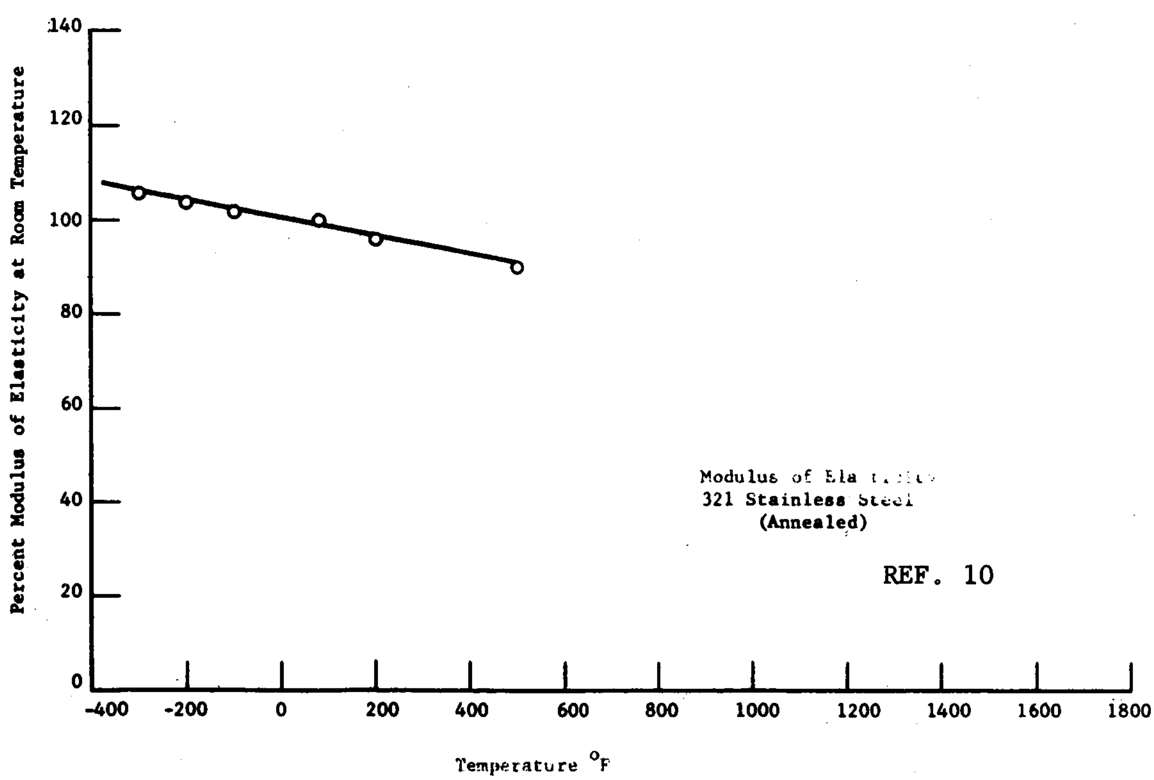

Figure 45 Modulus of Elasticity as a Function of Temperature - Stainless Steel 321

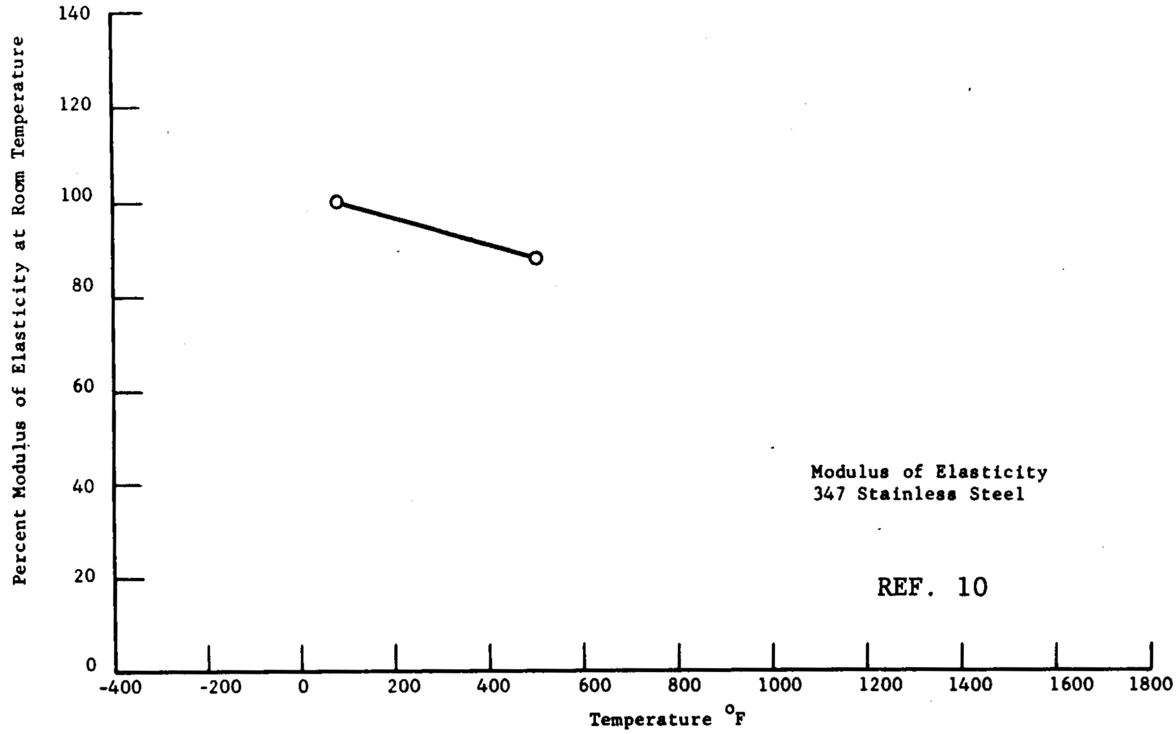

Figure 46 Modulus of Elasticity as a Function of Temperature - Stainless Steel 347

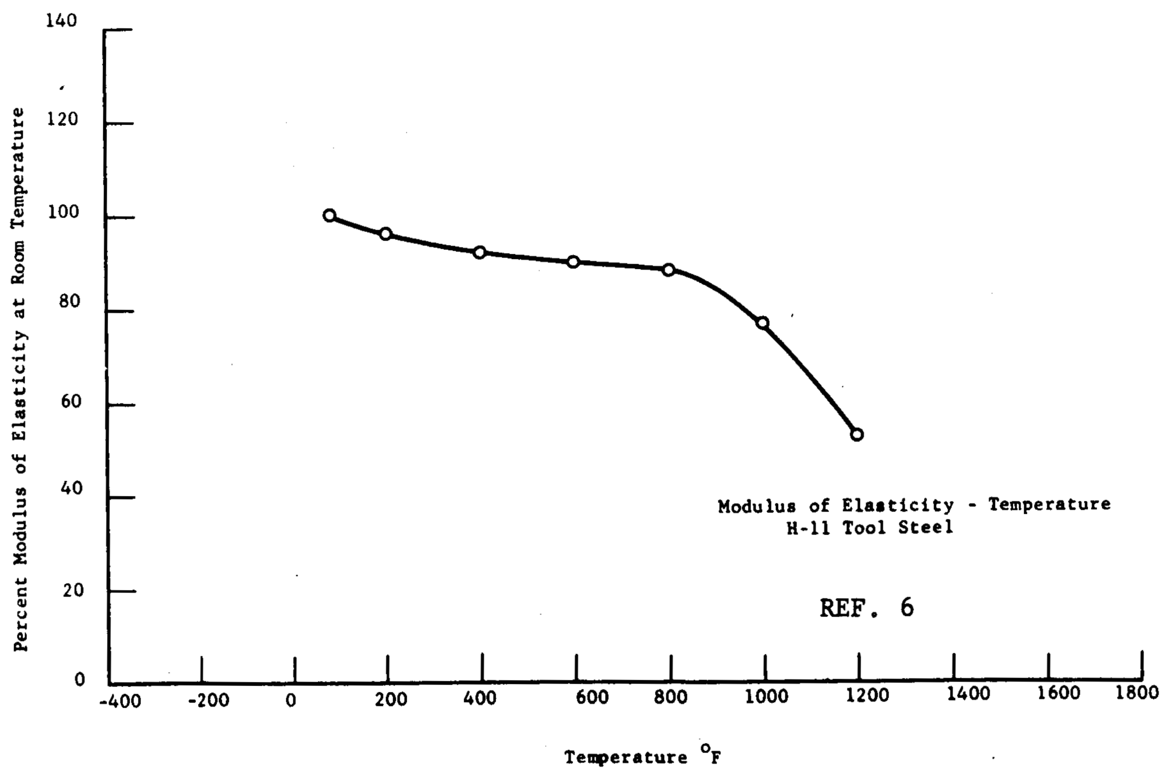

Figure 47 Modulus of Elasticity as a Function of Temperature - Tool Steel H-11

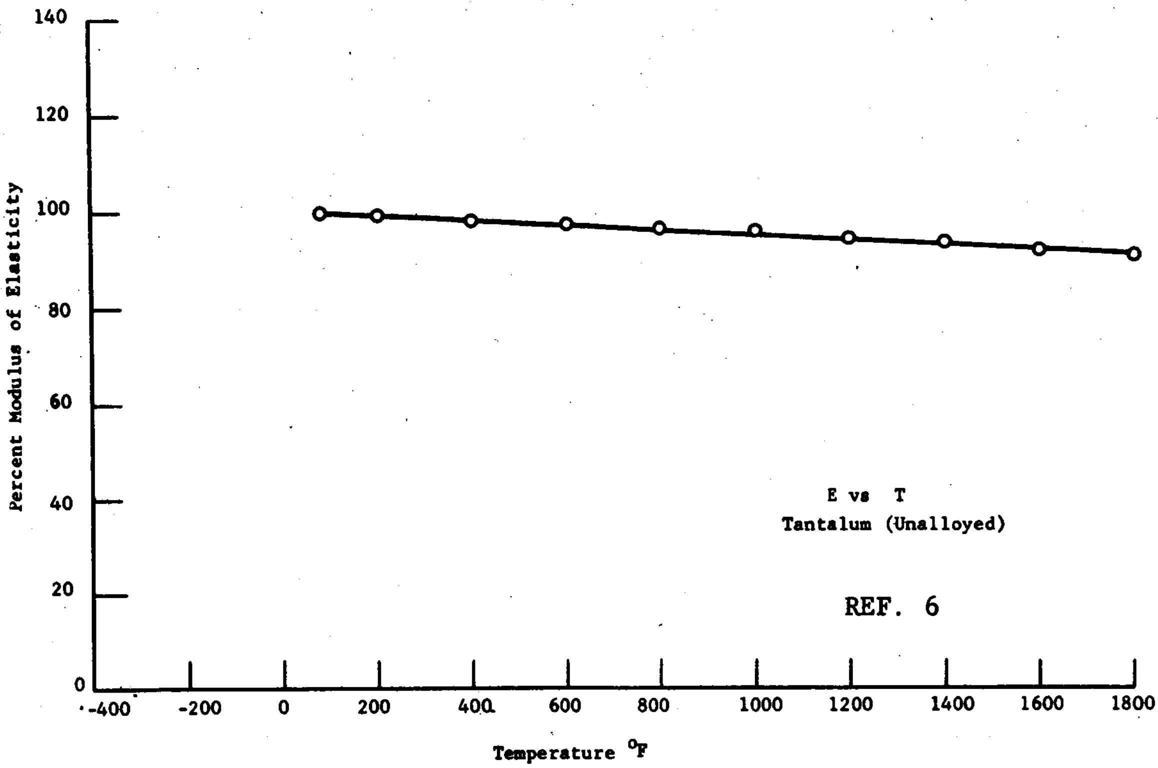

Figure 48 Modulus of Elasticity as a Function of Temperature - Tantalum

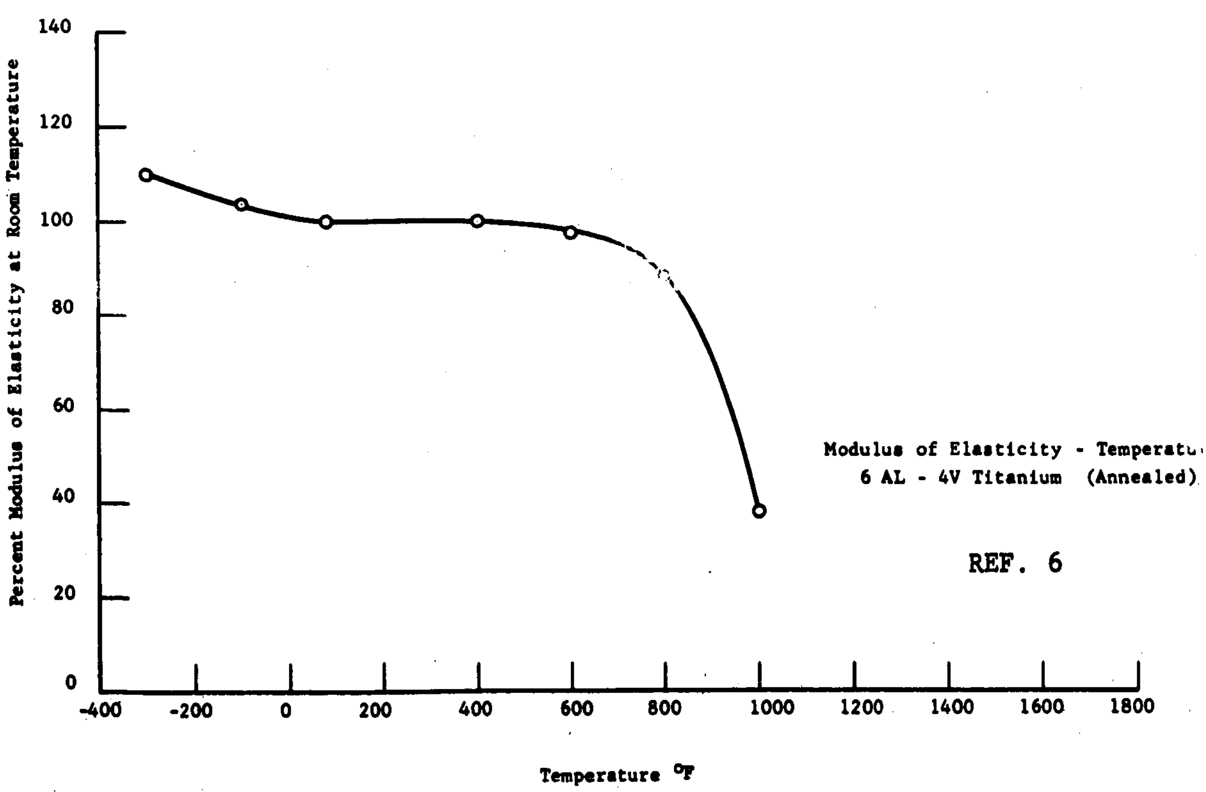

Figure 49 Modulus of Elasticity as a Function of Temperature - Titanium 6 AL - 4V

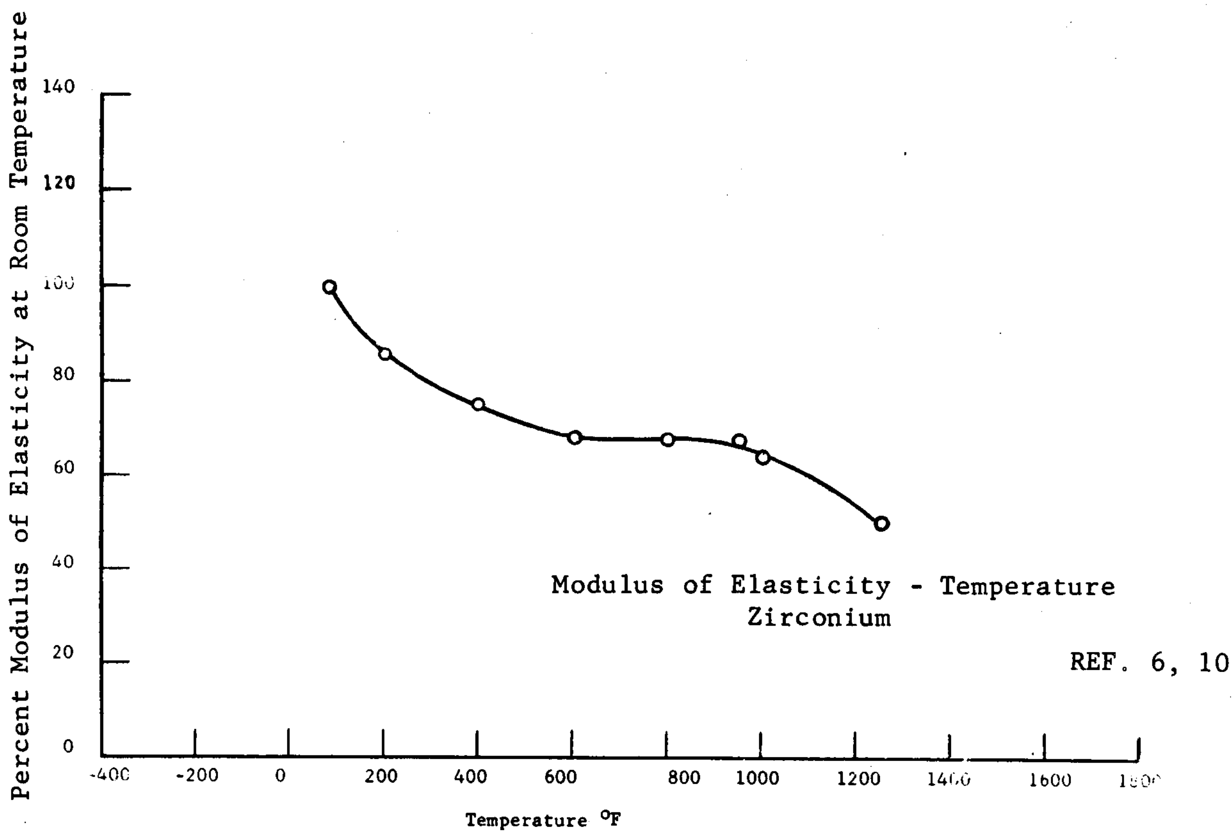

Figure 50 Modulus of Elasticity as a Function of Temperature - Zirconium

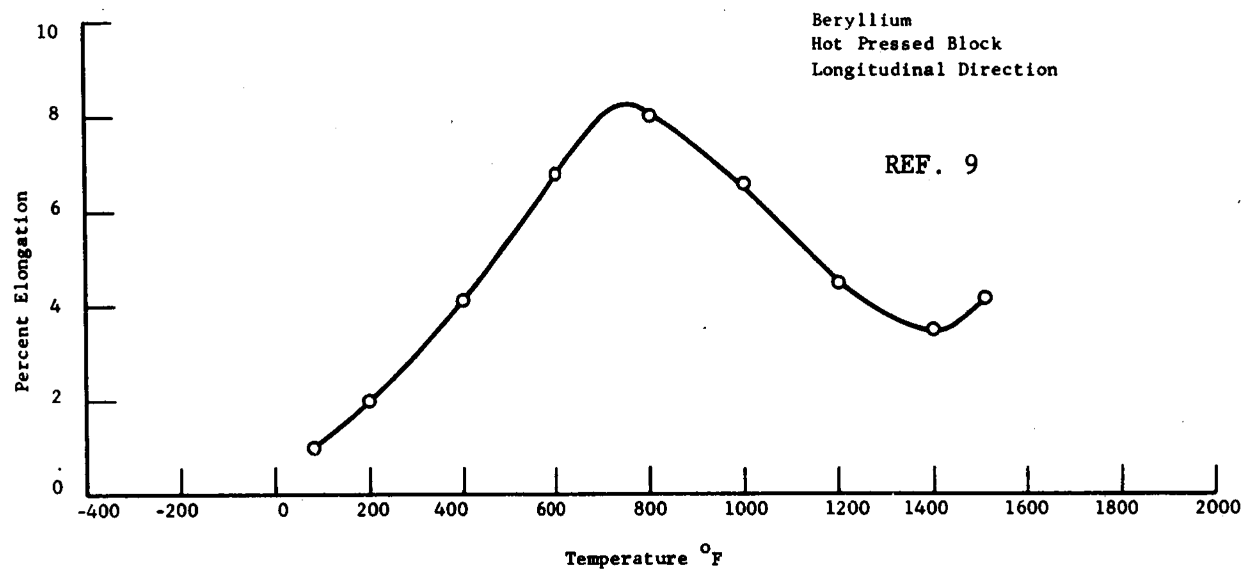

Figure 51 Elongation as a Function of Temperature - Beryllium

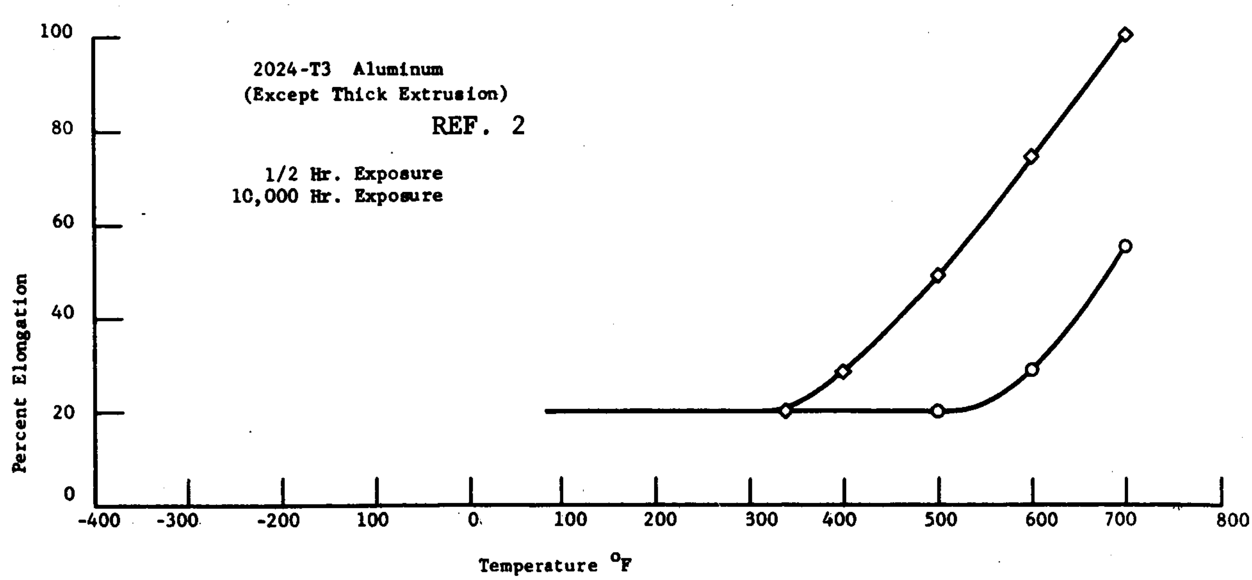

Figure 52 Elongation as a Function of Temperature - Aluminum 2024-T3

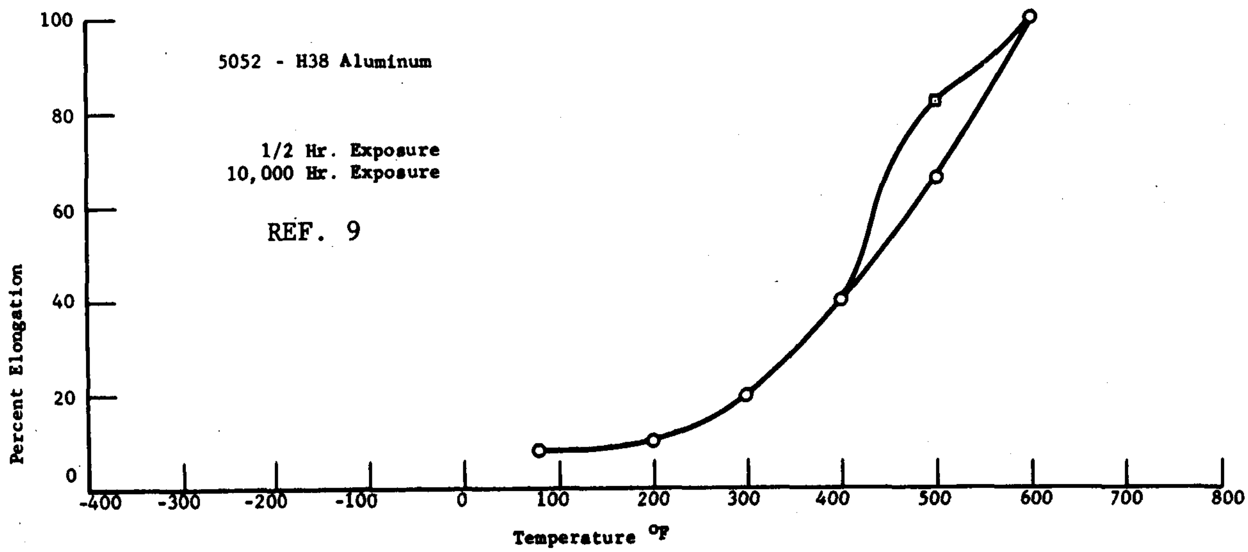

Figure 53 Elongation as a Function of Temperature - Aluminum 5052 - H38

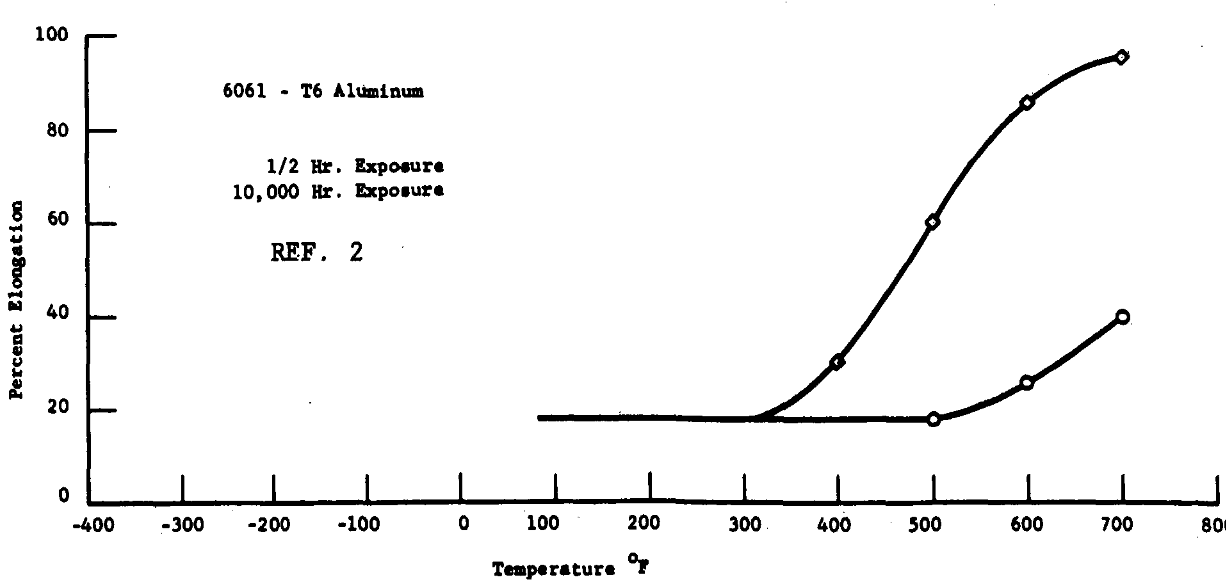

Figure 54 Elongation as a Function of Temperature - Aluminum 6061 - T6

on the behavior at low temperatures. For example, finer grain size in steels improves low temperature toughness.

The table in this section and the table showing the effect of temperature on ultimate tensile strength may be used to establish the low temperature limitations for the specific problem at hand.

Section 3

MATERIAL LIMITATIONS

Materials have been listed under material property headings in an orderly arrangement from highest to lowest (Tables XIV-XIX). The properties considered are ultimate tensile strength, yield strength, specific strength, machinability, useful temperature range, and corrosion resistance. Since this section is a rearrangement of information given in Sections 2 and 4, it is subjected to the same limitations as discussed in each section. Note that the corrosion resistance data is drawn largely from the experience of the chemical industry in transporting and storing these fuels, oxidizers, and monopropellants. The environments encountered have moderate temperature ranges and are not subjected to severe shock or vibration conditions.

Included in this section are the materials low temperature limitations. The major factors influencing the materials behavior at low temperatures are 1) crystal structure, 2) alloy content, and 3) microstructure. Face center cubic materials such as nickel, copper, aluminum, lead, and silver remain ductile at cryogenic temperatures while body center cubic materials like iron, molybdenum, tantalum, etc. show a marked decrease in ductility at low temperatures. Hexagonal crystal materials already show limited ductility at room temperatures.

The alloying agents have an influence on material properties at low temperatures. For example, as the nickel alloy is increased in steels ductility is retained to lower temperatures. A lower carbon content in sheet also improves cryogenic properties of steels.

Microstructure also greatly effects the low temperature mechanical properties of alloys, especially toughness. Therefore, heat treatment, cold working, shape of part, method of fabrication, etc. all have an affect upon the given size and boundaries, and hence have a direct affect

TABLE XIV TENSILE STRENGTH (ROOM TEMPERATURE)

	Tensile Strength (1000 psi)
Ultra High Strength Steel	
25 Ni	319
Modified H-11	311-295
Alloy Steels	
5150	312-116 (1)
4340	284-142 (1)
8650	282-123 (1)
4320	218-211
4280	207-205
8620	188-167
Titanium	
13 V, 11 Cr, 3 AL	240-190
6 AL, 4V	180-145
Rene' 41	206
Inconel X	162
Tantalum 10-W	160
A-285	150
Haynes 25	146
Monel 400	140-100
Duranickel	120-90
Hastelloy-X	114
19-9 DL	114
Columbium D31	100
Titanium (unalloyed)	100-60
Stainless Steels (17-14 Cu Mo, 304, 316, 321, 347)	92-85
Beryllium	90-60
Copper Alloys	
715 Cupro-Nickel	80
687 Aluminum Brass	60
365 Leaded Muntz	54
Nickel A (200)	75-55
Aluminum Alloys	
2024-T3	70
6061-T6	45
5052-H38	42
3003-H18	29
Zirconium	64
Tantalum (unalloyed)	60
Magnesium ZK60A-T5	50-53
Plastics	
Vinylidene Chloride	40-15
Nylon 6	11.3-10.2
ABS	8.5-7.5
Chlorinated Polyether	6
Kel-F	5.7-4.6
Teflon	3.5-2.5

(1) Spread in property values between hardened and annealed state

TABLE XV YIELD STRENGTH OF METALS (ROOM TEMPERATURE)

	Yield Strength 1000 psi
25 Ni Ultra High Strength	284
Alloy Steel 8650	250-114 (1)
Modified H-11 Alloy Steel	247-241
Alloy Steel 5150	250-102 (1)
Titanium (13 V, 11 Cr. 3 AL)	220-170
Alloy Steel 4340	228-130 (1)
Alloy Steel 4320	178-173
Titanium (6 AL, 4 V)	175-135
Tantalum 10 W	158
Rene' 41	154
Alloy Steel 8620	149-120
A-286	100
Titanium (unalloyed)	95-40
Inconel X-750	92
Columbium D31	90
Copper 715 (cupro-nickel)	73
19-9 DL	71
Haynes 25	67
Beryllium	55-45
Zirconium	53
Durnanickel	50-30
Aluminum 2024-T3	50
Tantalum (unalloyed)	48
Magnesium ZK60A-T5	44-40
Hastelloy X	43
Aluminum 6061-T6	40
Aluminum 5052-H38	37
Stainless Steel (17-14 Cu Mo, 304, 316, 321, 347)	42-35
Nickel 200	30-15
Aluminum 3003-H18	27
Copper 687 (Alum. Brass)	27
Copper 365 (Leaded Muntz)	20

(1) Spread in property values between hardened and annealed state

TABLE XVI SPECIFIC STRENGTH* OF METALS AND PLASTICS

	(1000 Psi/LB)
Titanium (13 V, 11 Cr, 3 AL)	1260
Titanium (6 AL, 4V)	1090
Ultra High Strength Steel 25 Ni	960
Ultra High Strength Steel Modified H-11	880
Alloy Steel 8650	880
Alloy Steel 4340	805
Beryllium	800
Rene' 41	686
Magnesium ZK60A-T5	665
Alloy Steel 4320, 4820	630
Titanium (unalloyed)	583
Alloy Steel 8620	526
Aluminum 2024-T3	500
Aluminum 6061-T6	400
Monel 400	400
Aluminum 5052-H38	370
A-286	350
Nylon 6	323
Inconel X-750	310
Columbium D-31	308
Aluminum 3003-H18	270
ABS Resins	266
Tantalum 10W	260
19-9 DL	247
Copper 715 (Cupro-Nickel)	226
Zirconium	224
Haynes 25	203
Duranickel	202
Hastelloy-X	174
Chlorinated Polyether	140
Vinylidene Chloride	133
Stainless Steel (17-14 Cu Mo, 304, 316, 321, 347)	121
Nickel 200	94
Copper 687 (aluminum brass)	90
Kel-F	88
Copper 365 (leaded muntz)	66
Teflon	51

*Specific strength, or strength-weight ratios, were obtained by dividing yield strength of metals and tensile strength of plastics by the density. In most cases, tensile strengths of plastics are roughly equal to their yield strengths and the comparisons are valid.

TABLE XVII MACHINABILITY*

	Index
Magnesium ZK60A-T5	500
Aluminum 3003,5052,6061	185
Aluminum 2024	150
Copper 365 Leaded Muntz	120
Alloy Steel 4320, 4340	51-62
Stainless Steel 347, 321	55
Alloy Steel 8620, 8650	45-61
Stainless Steel 304, 316	50
Alloy Steel 4820	45
19-9 DL	40
Copper 687 Aluminum Copper	30
Titanium Alloys	20-40
A-286	27
Copper 715 Cupro-Nickel	
Inconel X	15
Haynes 25	12

* Machinability index is based on AISI B1112 = 100

TABLE XVIII TEMPERATURE LIMITATION

Metals	Upper* °F	Lower °F
Tantalum	2200-2700	-
Haynes 25	1850-2250	-
Columbium	1950	-
Alloy steels	1400 to 2000	-
Ultra-High Strength Alloys		0
Fine grained carbon steels		-40
3.5% Ni steels		-150
5% Ni steels		-200
9% Ni steels		-320
A286 Mar aging Stainless Steel		-320
Stainless Steel 300 series		-450
Beryllium	1400 to 2100	-
Nickel Alloys	1200 to 2300	-450
Zirconium	1200 to 1450	-
Copper	800 to 1500	-
Titanium (unalloyed)	850 to 1400	-400
13V-11 Cr-3AL Heat treated		0
6AL 4V		-400
Aluminum Alloys 2024-T3, 6061T6, 5052-H38	775	-450
Magnesium	650	-

*
Temperatures given are annealing temperatures of the materials. Materials lose their strength as the temperature increases usually reaching unsatisfactory conditions before the annealing temperature is reached. In any event the material should not be exposed to annealing temperatures when in use. Large variations in annealing temperature accounts for various alloys.

Plastics	Useful temperature range	
Teflon (PTFE)	500	-450
Teflon (FEP)	400	-450
Kel-F (PTFCE)	400	-400
Chlorinated Polyether	300	
Nylon	250	
ABS	250	-40
Vinylidene Chloride	200	
Rubbers		
Silicone	500	-120
Viton	450	-50
Hypalon	300	-40
Neoprene	240	-40

TABLE XIX

CHEMICAL COMPATIBILITY OF CANDIDATE TUBE AND DUCT MATERIALS WITH SOME ROCKET PROPELLANTS

	Petroleum Fractions	Hydrogen (Liquid) H_2	Hydrazine N_2H_4	UDMH $(CH_3)_2N_2H_2$	Aerozine 50 50% N_2H_2 50% UDMH	Monomethyl Hydrazine $CH_3-N_2H_3$	Ammonia NH_3	Pentaborne B_5H_9	Oxygen (Liquid) O_2	Hydrogen Peroxide H_2O_2	Nitrogen Tetroxide N_2O_4	Nitric* Acid HNO_3	Fluorine F_2	Chloride Trifluoride CLF_3	Perchloryl Fluoride CLO_3F	Oxygen Difluoride OF_2	Nitrogen Trifluoride N_2F_4
ALUMINUM																	
2024-T3	C	A	D	C	D	C	A(10)(7)	A(2)	A(14)(2)	D	D	D	A(10)	B	B(1)	B(11)	-
3003-H18	A	-	B(1)	B	B(1)	B	A(10)(7)	A(2)	A(14)(2)	B(2)(9)	A(1)(9)	A(2)(9)	A(10)	B	B(1)	B	-
5052-H38	-	A	-	B	-	B	A(10)(7)	A(2)	A(14)(2)	B(2)(9)	A(1)(9)	-	-	-	-	-	-
6061-T6	A	-	A(1)	B	B(1)	B	A(10)(7)	A(2)	A(14)(2)	B(2)(9)	A(1)(9)	A(2)(9)	A(10)	B	B(1)	B	-
ALLOY STEEL																	
4340	A	A(13)	-	B(1)	-	D	A(10)	A	A(13)	D	A(2)	D	B(13)(15)	A(2)	B(1)	-	-
STAINLESS STEEL																	
304L	A	A	A(1)	B(1)	B(1)	B(1)	A	A	A	B(2)	A(2)	B(2)	B(10)	B	B	B	A
316	A	A	C(1)	B(1)	C(1)	B(1)	A	A	A	B(2)	A(2)	B(2)	B(10)	B	B	B	A
321	A	A	B(1)	B(1)	B(1)	B(1)	A	A	A	B(2)	A(2)	A(2)	B(10)	B	B	B	A
347	A	A	B(1)	B(1)	B(1)	B(1)	A	A	A	B(2)	A(2)	A(2)	B(6)(10)	B	B	B	A
17-14 CuNi	-	-	-	-	-	-	-	-	-	-	-	-					
A-286	A	-	C(1)	B(1)	C(1)	B(1)	-	-	-	B(2)	A(2)	B(2)	D	B	B	B	D
NICKEL ALLOYS																	
Inconel-X	A	A	B(1)	A	B(1)	A	-	-	A	D	A(1)	B(2)	A(10)	A	A	A	-
Hastelloy-X	-	B(15)	-	-	-	-	A(10)	A	A	D	B(1)	-	-	A	-	-	-
Rene' 41	A	B(15)	A(1)	B	B(1)	B	-	-	A	D	A(1)	B(2)	A(10)	A	A	A	-
METALLIC GASKETS																	
Indium	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lead	-	D	D	-	D	-	A(10)	-	-	D	A(6)	D	B(3)	-	-	-	-
Aluminum 1060	A	-	A(1)	B	B(1)	B	-	A(2)	-	A(2)(9)	A(1)(9)	A(2)(9)	A(10)	B	B(1)	B	-
Copper	D	-	D	D	D	D	A(10)	A	A	D	D	D	A(10)	B(2)	A(11)	A(11)	D
Nickel	A	A	C(1)	A	A	A	A(10)	A	-	D	D	D	A(10)	A(3)	A(11)	A(11)	A
PLASTICS																	
KEL-F	A	-	A(1)	A(1)	A(1)	A(7)	A	A(7)(15)	A(8)	B(2)(15)	A(7)	A	A(4)(11)	A(11)	A(11)	-	-
Teflon	A	A	A	A(1)	A(1)	A(7)	A	A(7)(15)	A(8)	B(2)(15)	A(7)	A	A(10)(11)	A(11)	A(11)	-	-
RUBBERS																	
Neoprene	B(15)	D	A(6)	D	D	-	B(6)	D	-	-	-	-	D	-	B(5)(10)	-	-
Silicone	D	A(13)	A(6)	D	D	-	B(6)	D	-	-	B(7)(15)	-	-	-	B(5)(10)	-	-
Viton	-	-	-	-	-	-	-	B(15)	A	-	-	-	-	-	A(10)	-	-
Hypalon	D	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

EXPLANATION OF SYMBOLS AND NOTATIONS

A Material suitable for unlimited service involving long-term storage of propellant.

B Material suitable for storage of propellant under limited conditions, and for short-term contact prior to storage of propellant.

C Material suitable only for short-term contact prior to use of propellant.

D Material not suitable for use with propellant.

(1) Service limited to 160°F maximum with dry propellant.

(2) Material must be suitably passivated prior to use with propellant.

(3) Service limited to 100°F maximum with dry propellant.

(4) Service limited to room temperature with dry propellant.

(5) Service limited to 390°F maximum.

(6) Service limited to 80°F but may be higher.

(7) Service limited to 160°F maximum.

(8) Not to be used with aluminum in liquid oxygen.

(9) Suitable only for short-time use in systems where metals other than aluminum alloys are also in contact with propellant because of resulting preferential chemical attack on aluminum alloys by propellant.

(10) Suitable for use with dry propellant.

(11) Service may be affected by high flow rates.

(12) Surfaces must be rust free for satisfactory use.

(13) Material is compatible but embrittles at cryogenic temperatures.

(14) Material is impact sensitive if stripped of its coating.

(15) Classification based on limited information and given a lower rating than it may be capable of.

(16) Duranickel was given the same rating as nickel since it contains 94% Ni and only 4.5 Al. Where Al is attacked and Ni is not, no rating is given since corrosion may occur.

(17) Service limited to 200°F.

(18) Use of all metals is contingent on suitable stabilization. Extended service of stainless steels in these propellants may result in heavy deposits of fluorides. Systems utilizing stainless steel should be flushed after use at high temperature to remove fluoride deposits.

(19) May be susceptible to chemical attack by propellant.

(20 Information on Alkyl Borane fuels is limited because of government classification.

(21) May be suitable for short exposures under controlled conditions where material is not allowed to become oxidized. It may decompose propellant.

(22) Most commonly used material of construction for propellant storage facilities.

(23) Specified satisfactory for use by the Working Group on Safety Regulations for Liquid Propellants.

(24) Except furfuryl alcohol

(25) Must be free of all traces of rust.

(26) Service limited to gaseous propellant only.

(27) Not acceptible for liquid propellant.

- Indicates lack of data to make evaluation.

* Alloys considered in this Guide Manual

Section 4
COMPATIBILITY

If there is no corrosive attack by the propellants, fuels, oxidizers, or monopropellants on its container, and if there is no decomposition of the propellant caused by the container, the propellant and container are considered to be compatible. Several propellants are easily decomposed by common materials of construction. When selecting a container material for these propellants, the effect of the material on the decomposition of the propellant is of prime importance. Propellants exhibiting the susceptibility to decomposition are pointed out in the discussion of propellants at the end of this section. However, corrosion is the major cause of incompatibility of a propellant handling system. Corrosion* may be defined broadly as the destruction or deterioration of metal by direct chemical or electrochemical reaction with its environment.

CORROSION

Corrosion occurs because a metal is inherently unstable tending to revert toward a stable state of which the metallic ores are familiar examples. Corrosion is superficial, but sometimes attacks areas of weakness such as grain boundaries where there is a difference in resistance to attack or local electrolytic action. Recent work on the fundamentals of corrosion has shown that the essential phenomena are the same for all metals and alloys, differing only in degree, not in kind. The driving force of the corrosion reaction between metal and environment is electrochemical (Reference 21).

*A glossary of terms used in corrosion has been prepared by a committee of the American Electrochemical Society (1946).

Corrosion may be classified (Reference 4) with respect to its outward appearance into five main types which are:

1. Uniform attack - Examples are rusting of iron, tarnishing of silver, "fogging" of nickel and high temperature oxidation of metals. Metals used to handle corrosive fluids are classified into three groups depending on their corrosion rates and intended application. The classifications are:

   (a) When the corrosion rate is less than 0.005 inches penetration per year (0.005 ipy).

      Metals in this category have good corrosion resistance and may be used for critical parts such as valve seats, pump shafts, springs, and seals.

   (b) 0.005 to 0.05 ipy.

      Metals in this category are satisfactory if high rate of corrosion is acceptable, i.e. tanks, piping, valve bodies, etc.

   (c) 0.05 ipy and higher.

      Usually unsatisfactory.

2. Local Attack - A localized type of attack where the rate of corrosion is greater at some areas than others is called pitting. Also included in this type of corrosion are impingement attack or corrosion-erosion resulting from high velocity liquids, fretting corrosion which results from a slight relative motion (vibration) of two substances in contact, and cavitation-erosion which results from cavitation at the liquid-metal interface.

3. Parting and Dezincification - Parting is the preferential corrosion of one or more of the reactive components of the alloy leaving a porous residue and affecting the mechanical properties of the material. When parting occurs in brasses, it is called dezincification because it is the zinc alloy that is preferentially attacked.

4. Intergranular corrosion - This is a localized attack at the grain boundaries resulting in the loss of strength and ductility. The attack is often rapid, penetrating deeply into the metal, and sometimes causes catastrophic failures.

5. Cracking - If a metal cracks when subjected to repeated or alternating tensile stresses in a corrosive environment, it is said to fail by corrosion fatigue. When subject to a constant high tensile stress in specific corrosive environment, the failure is called stress corrosion cracking.

PASSIVITY

A passive metal is one that is active in the Emf series but which corrodes nevertheless at a very low rate. The underlying property from which many structural metals such as aluminum, chromium, and stainless steels obtain their natural corrosion resistances is passivity. Passivity may be defined for a metal active in the Emf series, or an alloy composed of such metals, as electrochemical behavior typical of an appreciably less active or noble metal (Reference 22) Examples are chromium, nickel, molybdenum, titanium, zirconium, stainless steel, monels, and others which are naturally passive in air. Also included are metals passive in passivator solutions like iron in dissolved chromates.

There are two commonly expressed theories of passivity. The first states that a passive film is always a diffusion barrier of reaction products such as metal oxides which separate metal from its environment and slows the rate of reaction. This theory is referred to as the oxide film theory. The second is known as the "absorption theory of passivity" and states that passive metals are covered by a chemisorbed film or passivating ions. Both theories are based on a diffusion barrier film which accounts for the passivity of metals.

CORROSION CONTROL

The rate of corrosion may be controlled by cathodic and anodic (passivating) protection, applying resistant coatings, adding inhibitors and passivators to the contained fluid, and alloying the metal for resistance. Cathodic protection is one of the most commonly used and one of the more effective methods of corrosion control. An externally applied electric current polarizes the cathodic elements of local action cells, which are the cause of the corrosive action, to the open-circuit potential of the anodes (Reference 20). The surface becomes equipotential and corrosion currents no longer flow. This method of corrosion control may find limited use in propellant transfer system since many propellants may be detonated with an electric spark or static electricity.

Coatings may be metallic, organic, and inorganic. They possess the disadvantages of possible porosity, susceptibility to damage during shipment or use, and, if metallic, to galvanic corrosion with the base material. Metallic coatings are either noble or sacrificial. Noble coatings are noble in the galvanic series with respect to the base metal and are resistant to corrosive attack. The coating may be undermined due to corrosion of the base metal by corrosive fluid seeping through the pores of the coating. In sacrificial coatings, the coating is attacked and sacrificed to save the base metal.

Inorganic coatings consist of glass liners, enamels, cement, and chemical conversion coatings. Chemical conversion coatings are protective coatings formed in situ by chemical reaction with the metal surface. An example is the iron fluoride formed on steel containers when filled with hydrofluoric acid.

Organic coatings consist of paint and plastic liners. Plastic liners have excellent potential for corrosion control in propellant handling systems. Teflon is resistant to most propellants and being a thermoplastic it can be jointed by applying heat. Caution should be exercised with Teflon because of its large diffusion coefficient.

Another method of control for reducing corrosion rates is by adding inhibitors to the contained fluid. An inhibitor is a chemical substance which when added in small concentrations to an environment effectively decreases the corrosive nature of the environment. An example is the addition of 0.1% of hydrofluoric acid to fuming nitric acid in steel containers. One type of inhibition results from contact with the metal surface of depolarizers, producing high density currents at residual cathodic areas forming a protective film similar to the films on passive metals.

Alloying is an effective means of improving the resistance of metals to corrosive environments. The corrosion resistance improvement of iron with the addition Cr and Ni forming stainless steels is a well-known example.

METALS IN CORROSIVE MEDIA

This section briefly outlines the behavior of common materials of construction when exposed to a corrosive environment. Material presented in this section is largely taken from Uhlig and Speller, references 3 & 57 respectively.

Stainless Steels

Stainless steels exist as ferritic, austenitic, or martensitic grade alloys and are designated as 200, 300, and 400 series respectively. They are susceptible under some conditions to intergranular corrosion, pitting or crevice corrosion, and hydrogen cracking.

Intergranular corrosion in stainless steels is usually caused by precipitation of a complex chromium carbide in the grain boundaries and is of primary concern in austenitic stainless steels. Susceptibility to intergranular corrosion is a function of temperature, time at temperature, and carbon content. The sensitizing temperature range is 750°F to 1050°F. When a 300 series alloy is heated to and above this temperature range, it should be rapidly quenched. Damage may occur upon exposure to a corrosive environment, the degree of damage being dependent on the environment and the temperature and time of exposure. Effective means of avoiding intergranular corrosion are (1) proper heat treatment, (2) reduction of the carbon content to below 0.03% as designated by L (314L, 316L), and (3) addition of titanium or columbium which are known as stabilizing grades (321, 347, 348).

Pitting or crevice corrosion occurs primarily in environment of chloride and bromide ions. Any crevice whether between two metal surfaces or between a metal and a non-metal is the most likely place where the pit will initiate. Crevice corrosion may be avoided by cathodic protection, adding alkaline inhibitors to the chloride environment, operating at the lowest temperature, and maintenance of uniform oxygen or oxidizing concentrations.

When subjected to applied or residual tensile stresses, stainless steels may crack transgranularly when exposed to certain environments. Environments that are critical in causing cracking are different for austenitic and martensitic or ferritic stainless steels. For austenitic stainless steel (300 series) the most damaging ions are the hydroxyl (OH^-) and the chloride ($C\ell^-$). Cracking, however, does not tend to occur in ferritic or martensitic stainless steels in a chloride environment; therefore, martensitic stainless steels are preferred in chloride atmospheres. Martensitic stainless steels are, however, sensitive to cracking when exposed to slightly acidic solutions to a degree highly dependent upon prior heat treatment and hardness. In austenitic stainless steel, nitrogen is the element largely responsible for stress cracking susceptibility, and stabilizing additions such as molybdenum, titanium, and columbium, have no effect on reducing the susceptibility to stress corrosion. Stress corrosion can be reduced or eliminated in austenitic stainless steels by (1) keeping the operating temperature below 80^oC, (2) cathodic protection, (3) elimination of chloride ion, (4) avoiding high concentrations of hydroxyl ions, and (5) using an alloy containing 50% nickel or reducing the nitrogen content. Use of a martensitic or ferritic stainless steel may be a preferable alternative in some applications.

Aluminum

Aluminum has a sensitivity to corrosion by alkalies and to attack by traces of cooper ions in aqueous media. In addition aluminum is rapidly attached by mercury metal and ions, and is attached by anhydrous chlorinated solvents such as $CC\ell_4$, ethylene dichloride, and propylene dichloride. Aluminum receives its corrosion resistance from an oxide film that can be made thicker by anodizing. In general aluminum is resistant to (1) NH_4OH, both hot and cold, (2) fatty acids, (3) nitric acids with concentrations above 80% at temperatures up to 120^oF, (4) distilled water, (5) atmospheric exposure, (6) sulfur atmospheres, and (7) fluorinated refrigerant gases. Aluminum alloys are generally not resistant to (1) strong acids such as $HC\ell$, HBr, H_2SO_4, HF, $HC\ell O_4$, H_3PO_4, (2) alkalies such as lime and concrete, (3) mercury, (4) sea water, (5) waters containing heavy metal ions, (6) chlorinated solvents, and (7) anhydrous ethyl, propryl, or butyl alcohols at elevated temperatures.

Magnesium

The corrosion resistance of magnesium depends on the purity of the metal. In general, magnesium alloys are resistant to (1) atmospheric exposure if stress relieved to avoid stress corrosion cracking, (2) distilled water, (3) hydrofluoric acid (pitting may occur at water-air interface), and (4) alkalies. Magnesium alloys in general are not resistant to (1) waters containing heavy metal ions, (2) sea water, (3) inorganic or organic acids and acid salts, (4) methanol (anhydrous), (5) leaded gasolines, and (6) Freon ($C\,C\ell_2\,F_2$).

Copper

Copper is noble to hydrogen in the emf series and thermodynamically stable with no tendency to corrode in water and in non-oxidizing acids free of dissolved oxygen. In oxidizing acids or in aerated solutions containing ions which form Cu complexes, corrosion can be severe. Copper is susceptible to impingement attack by high velocity water or aqueous solutions and stress corrosion cracking. Dezincification of brasses is a special problem. In general, copper is resistant to (1) sea water, (2) fresh water both hot and cold, (3) non-oxidizing acids, and (4) atmospheric exposure. In general, copper is attacked by (1) oxidizing acids, (2) NH_4OH (plus O_2), (3) high velocity aerated waters and aqueous solutions, (4) oxidizing heavy metal salts, and (5) H_2S, sulfur, and sulfur compounds.

Nickel

Nickel is active in the emf series with respect to hydrogen, but noble with respect to iron. It corrodes by pitting when exposed to sea water but is not subject to stress corrosion cracking except in high concentrations of alkali. In general, nickel is resistant to (1) alkalies, (2) extremes in temperature, (3) dilute non-oxidizing inorganic and organic acids (with improved resistance if acids are deaerated), and (4) the atmosphere. Nickels corrode when exposed to (1) oxidizing acids such as HNO_3, (2) oxidizing salts $FeC\ell_3$, Cu $C\ell_2$, etc.), (3) aerated ammonia hydroxide, (4) alkaline hypochlorates, (5) sea water, and (6) sulfur or sulfur containing reducing environments.

Titanium

Titanium is active in the emf series and is readily passivated in aerated aqueous solutions, including dilute acids and alkalis. It is resistant to pitting and crevice corrosion in sea water and resistant to stress corrosion cracking in a variety of chemical media with the exception of fuming nitric acid. It has been reported that titanium, presumably sponge, in contact with liquid oxygen is sensitive to detonation by impact. In general, titanium is resistant to (1) sea water (including high velocity), (2) wet chlorine (may ignite in dry $C\ell_2$), (3) nitric acid except fuming HNO_3, (4) oxidizing salts, and (5) hypochlorites. Titanium will corrode in (1) aqueous HF, (2) fluorine, (3) $HC\ell$, (4) H_2SO_4, (5) oxalic, formic acids, (6) concentrated hot alkalies, (7) molten salts, and (8) high temperature exposure to air, nitrogen, or hydrogen which leads to embrittlement.

Zirconium

Zirconium is an active metal in the emf series, but normally exhibits very stable passivity. The chemical industry has used zirconium primarily in corrosive atmospheres since it possesses outstanding corrosion resistance to alkalies at all concentrations up to the boiling point. Zirconium generally is resistant to 1) alkalies at all concentrations, 2) hydrochloric acid, 3) nitric acid, 4) sulfuric acid, 5) phosphoric acid, 6) boiling formic, acetic, lactic, or citric acids, and 7) sea water. Generally zirconium is reactive with 1) oxidizing metal chlorides, 2) HF, 3) wet chlorine, 4) O_2, N_2, or H_2 at elevated temperatures, 5) aqua regia, 6) boiling trichloroacetic acid, and 7) boiling $CaCl_2$ solutions.

Tantalum

Tantalum exhibits the most stable passivity among known metals. It retains passivity in boiling acids such as HCl, HNO_3, and H_2SO_4 and in moist chlorine or $FeCl_3$ solutions at above room temperatures. Tantalum is generally resistant to 1) hydrochloric acid at all concentrations up to boiling point, 2) nitric acid all concentrations, 3) sulfuric acid, 4) chromic acid, 5) phosphoric acid, 6) halogen gases, 7) aqua regia, 8) oxidizing metal chlorides, and 9) organic acids. In general it is attacked by 1) alkalies, 2) HF and florides, 3) fuming sulfuric acid, and 4) O_2, N_2 or H_2 at elevated temperatures.

PROPELLANTS

This section presents a limited discussion of fuel and oxidizer properties that are of interest to the designer selecting a material for a propellant handling system. The chemical behavior of the propellant that may affect the container material are pointed out along with its boiling and freezing temperatures. Materials of construction classified as satisfactory by use by the Working Group on Safety Regulations for Liquid Propellants are given along with a brief discussion. The information presented in this section was taken from "The Handling and Storage of Liquid Propellants" Manual (Reference 17).

Alcohols

Chemical

Considered in this group are high concentrations (99% by volume) of Methyl, Ethyl, Isopropyl, and Furfuryl alcohols. Their boiling point, freezing point, critical temperature, and critical pressure are given in the Table below:

	Boiling	Freezing	Critical Temperature	Critical Pressure
Methyl alcohol	148°F	-144°F	464°F	1142 psig
Ethyl alcohol	173	-174	470	913
Isopropyl alcohol	180	-129	455	764
Furfuryl alcohol	338	-26	---	

Alcohols are excellent solvents and flammable liquids which will react vigorously with strong mineral acids or strong organic acids. They are not hypergolic with nonfluorinated oxidizers; however, furfuryl alcohol is hypergolic with fuming nitric acids. Methyl alcohol dissolves magnesium and its alloys. All liquid alcohols are insensitive to mechanical shock, but when mixed with oxidizers they form a mixture that can be exploded by impact, heat, or an electric shock.

Materials of Construction

All transfer and storage systems must be kept clean and free from combustibles. Steel is the most commonly used material for drums, storage tanks and permanent storage facilities. Stainless steel and aluminum may also be used.

The materials listed below are non-metals which are acceptable for use

Polyvinyl chloride

Neoprene } except for furfuryl alcohol
Rubber }

Kel-F

Teflon

Polyethylene

Asbestos gasket material

Alkyl Boranes (HiCal-3, HEF-2, HEF-3):

Chemical

Because of the lack of unclassified information, in handling these propellants users are cautioned against extrapolating this information, although it is believed to be accurate. Alkyl borane fuels are mixtures of alkylated boron hydrides which react violently with oxidizing materials and hydrazine. Slow reactions with water release hydrogen which may build up pressure during storage. Although Alkyl boranes are insensitive to shock they may decompose under storage conditions.

Materials of Construction

Alkyl borane fuels have been successfully handled during recent years. Since they are comparatively new fuels, not all conditions of handling have been evaluated. Therefore, fuel users should develop handling techniques appropriate for their operations.

Experience indicates that boron hydrides are not corrosive to most metals. Nearly all common metals can be used in storage and transfer systems. Some metals that have shown satisfactory performance with HiCal-3 are

Steel	Copper	Lead	Tantalum
Nickel	Aluminum	Titanium	Stainless Steel

Due to the variable nature of service for which non-metals are used, it is undesirable to be specific regarding their performance. Some non-metals found to be compatible are:

Teflon, Nylon, Fluororubber, Kel-F.

Non-metals found to be unsatisfactory for service and which should be avoided are:

Natural Rubber, Neoprene, Silicone Rubber.

Anhydrous Ammonia (NH_3):

Chemical

Boiling Point	$-28^{o}F$
Freezing Point	$-108^{o}F$
Critical Temperature	$270^{o}F$
Critical Pressure	1620 psig

Anhydrous ammonia is a highly reactive, basic, reducing agent. The rate of corrosion is dependent upon its water content and temperature. Moist ammonia corrodes copper, tin, zinc, and many alloys particularly copper alloys. Ammonia is insensitive to shock and thermally stable up to $950^{o}F$. When in contact with other chemicals including mercury, chlorine, iodine, bromine, calcium, silver oxide, or hypochlorite, explosive compounds can be formed.

Materials of Construction

Moist ammonia is generally more corrosive than dry ammonia. Although it will not normally corrode iron, steel, or aluminum, it will react rapidly with copper, brass, zinc, and many other alloys especially copper alloys. Approved metals are:

1) Anhydrous ammonia (Dry)

Stainless steel	Silver	Aluminum (below 150°F)
Carbon steel	Platinum	Tantalum
Nickel alloys	Gold	

2) Ammonia (Moist)

Inconel	Platinum	Stainless steel(300 & 400 series)
Gold	Tantalum	Steel (ambient temperature)
		Aluminum (ambient temperatures)

Some approved non-metals are:

Teflon, Kel-F, Glass, Polyethylene, Silicone (room temperature).

Materials found to be unacceptable when used with ammonia are:

Copper, Neoprene, Vinylidene Chloride

Chlorine Trifluoride (ClF_3):

Chemical Nature

Boiling Point	53°F
Freezing Point	-105°F
Critical Temperature	345°F
Critical Pressure	823 Psig
Concentration	minimum purity 99%

Chlorine trifluoride is a corrosive oxidizing agent similar to fluorine in reactivity. It is hypergolic and reacts violently with most fuels but is stable when subjected to mechanical shock, heat, and electric spark. A vigorous reaction occurs when placed in contact with water, most metals, and metal oxides at elevated temperatures.

Materials of Construction

Metals such as copper, silver solder, brass, steel, magnesium, aluminum, Monel, and nickel are satisfactory for use with chlorine trifluoride because of the formation of a passivating fluoride film. However, Monel and nickel are preferred because of their resistance to hydrogen fluoride and hydrogen chloride which is formed on reaction of chlorine trifluoride with water. Cleansing and passivating treatments similar to those described for metals that are used to contain fluorine must be used for chlorine trifluoride systems to reduce the possibility of rapid reactions.

Approved non-metals which may, however, ignite when heated are:

Neoprene (clothing only)

Kel-F, Teflon } Not recommended for flow conditions

Pyrex Glass

Materials unacceptable when used with liquid chlorine trifluoride are:

Inconel X, Hastelloy X, Titanium

Ethylene Oxide (C_2H_4O):

Chemical

Boiling Point	51°F
Freezing Point	-168°F
Critical Temperature	380°F
Critical Pressure	1028 Psig

Ethylene oxide is a monopropellant whose vapor is flammable in air if the concentration is above 3%. Liquid ethylene oxide itself is not shock sensitive, but its vapors explode when exposed to an electric spark, static electricity, excessive heat, open flame, or detonating agents. Mixtures of vapor and air are more explosive then vapor alone. Decomposition and/or polymerization may occur violently when in contact with a catalytic surface, such as anhydrous chlorides of iron, tin, and aluminum, oxides of iron and aluminum, metallic potassium, alkali metal hydroxides, acid, and organic bases. Reaction may be explosive at temperatures above 85°F.

Materials of Construction

All transfer and storage systems should be grounded to avoid uncontrolled explosion from an electric spark or static electricity. Approved metals for the transfered and storage of ethylene oxide are:

Mild steel properly protected from corrosive atmosphere to prevent formation of rust.

Stainless steel

Pure aluminum (99.6% pure or better)

Metals that should not be used to handle ethylene oxide are:

Copper and copper alloys

Magnesium and magnesium alloys

Steel and iron containing any trace of rust

Silver and silver alloys

The non-metals approved for service are:

$$\left.\begin{array}{l}\text{Teflon}\\ \text{Kel-F}\\ \text{Glass}\end{array}\right\}\ \text{Temperatures below } 160^{\circ}\text{F}$$

Nylon - Intermittent service at ambient temperatures only.

Fluorine:

Chemical

Boiling Point	$-306^{o}F$
Freezing Point	$-363^{o}F$
Critical Temperature	$-200^{o}F$
Critical Pressure	749 Psig

Fluorine is the strongest oxidizing agent and one of the most reactive materials known. Under proper conditions, it reacts with every known element except most of the inert gases. Unconfined fluorine is stable to shock, heat, and electric spark. However, containers confining fluorine must not be subjected to shock or heat, as a violent reaction with the container is possible. Fluorine is hypergolic with water vapor, ammonia, hydrogen, with most fuels and most organic vapors.

Materials of Construction

Cleanliness is essential for any fluorine system. If the metal surfaces are contaminated with organic substances, such as oil and grease, and comes in contact with fluorine or most any strong oxidizer, local hot spots may be formed which may cause a violent failure of the encasing material. Handling systems for fluorine should first be cleaned to remove all contaminates and then passivated with fluorine diluted with an inert gas.

When selecting a material for a fluorine system two factors must be considered: 1) resistance to fluorine attack and 2) mechanical strength at cryogenic temperatures. As a general rule, metals with low corrosion rates of atmospheric conditions and with high kindling temperatures are resistant to fluorine. Resistance is provided by the formation of a nonvolatile and adherent metal fluoride film. No data are available on the effects of fast moving streams of propellants which might disturb the passivated protective fluoride film and thus increase the corrosion rate. Metals approved for fluorine service are:

1) Gaseous fluorine

Nickel	Copper	Titanium
Monel	Aluminum	Zirconium
Stainless Steel (300 series)	Magnesium	Low Carbon Steels

2) Liquid fluorine

Monel

Stainless Steel (304, 321, 347; 347 is crack sensitive)

Since moisture is usually present, Monel is recommended as a construction material since it is resistant to both fluorine and the hydrofluoric acid formed when fluorine reacts with water.

Non-metals that will satisfactorily handle gaseous fluorine at moderate pressure and flow rates are:

Teflon (below 390°F)

Kel-F (at room temperatures)

Materials not acceptable for handling fluorine are:

Plastics

Zirconium Not acceptable when handling liquid fluorine

Titanium

Prolyethylene

Neoprene

Rubber

Hydrazine (N_2H_4):

Chemical

Boiling Point	236°F
Freezing Point	35°F
Critical Temperature	716°F
Critical Pressure	2120 Psig

Hydrazine is a strong reducing agent, weakly alkaline, and very hygroscopic. When in contact with metal oxides and oxidizing agents it will ignite. It decomposes on contact with such metals as iron, copper, molybdenum, and their alloys. Liquid hydrazine is insensitive to shock or friction but its vapors can be exploded by an electric spark or by an open flame. Hydrazine is a stable liquid over a wide range of temperatures. It contracts when freezing and its chemical properties are unaffected by freezing. Thermal decomposition begins at about 320°F.

Materials of Construction

When selecting a material for a hydrazine handling system, two factors must be considered: 1) resistance of the material to hydrazine and 2) the effect of the material and/or corrosion products on rate of decomposition of hydrazine. The specific application is a major factor in determining the acceptability of a material for hydrazine use. Metals that may be used with hydrazine are:

Stainless steel 303, 304, 316, 321, and 347

Nickel, aluminum 2S and 3S, Titanium 6AL-4V, and Tantalum

The following materials should not be used:

Hastelloys	Magnesium
Monel	Stainless steels contain more than 0.5% Mo
Aluminum 40E	Zinc
Lead	Copper and its alloys
Iron	

For certain applications there may be specific exceptions to the lists of metals given above.

Non-metals acceptable for use with hydrazine are:

Teflon
Polyethylene (high density)
Kel-F (unplasticized)

Hydrocarbon Fuels:

Chemical

Considered in this group are petroleum fractions of which only JP-4, JP-5, and RP-1 will be considered. JP-4 and JP-5 grades are aircraft turbine and jet engine fuels while RP-1 is a rocket engine fuel. The JP-5 and RP-1 fuels may be described as a high-boiling kerosene fractions, and JP-4 as a wide cut containing both kerosene and gasoline fractions. Hydrocarbon fuels react only with strong oxidizing agents or at extreme temperatures and pressures. They are insensitive to mechanical shock as liquids but are sensitive as vapor air mixtures.

		JP-4	JP-5	RP-1
Boiling point	°F	225 to 525	390 to 550	350 to 525
Maximum freezing point	°F	-76	-40	-40
Minimum flash point	°F	-	140	110
Autoignition temperature	°F	468	-	-

Materials of Construction

Storage tanks, associated piping and fittings, pumping equipment, valves, and other metal parts are normally made of steel which meets the appropriate mechanical specifications. Copper alloys (brass, bronze, and beryllium copper) should not be used in continual contact with the hydrocarbon fuels since they promote gum formation. Brief contact such as with hose nozzles is harmless.

Non-metals approved for use are:

Fluorocarbons (Teflon and Kel-F)

Polyethylene

Polyamides (Nylon)

Neoprene

Buna-N

Vinyls

Liquid Hydrogen:

Chemical

Boiling Point	-423°F
Freezing Point	-435°F
Critical Temperature	-400°F
Critical Pressure	180 Psig

Liquid and gaseous hydrogen at low temperatures is considered to be non-corrosive and will react violently with strong oxidizer. It will ignite very easily with oxygen and spontaneously with fluorine and chloride trifluoride. When allowed to evaporate, it becomes highly combustible with air over a wide range of mixture.

Materials of Construction

The retention of structural properties at cryogenic temperatures and ability to withstand thermal stresses produced by a large temperature change, are the most important factors when selecting a material for a hydrogen handling system. The ferrous alloys with the exception of austenitic nickel-chromium alloys (300 series stainless steel) lose their ductility at low temperatures. Metals suitable for service are:

Stainless steel (300 series)	Monel
Copper	Aluminum and most of its alloys
Bronze	Some nickel alloys
Brass	Cobalt alloys

Organic materials are limited because of the effect of low temperatures on their physical properties. Warm joints are used to avoid temperature effects on the gasket material. Only hydrogen gas contacts the gasket. Non-metals approved for use are:

Teflon

Kel-F

Nylon

Hydrogen Peroxide (52 to 100% H_2O_2 By Weight:

Chemical

Boiling Point	258 to 302°F (function of concentration)
Freezing Point	-40 to 31°F (function of concentration)

Hydrogen peroxide is a monopropellant and an active oxidizing agent. It is also an energy-rich material which decomposes yielding water, oxygen, and heat. When decomposed by a catalyst, it generates heat rapidly and at solution concentrations above 67%, enough heat is generated to raise the temperature of the solution to its boiling point. Hydrogen peroxide is hypergolic with hydrazine. When alone it is insensitive to shock waves and impact, but mixtures of appropriate organic materials with hydrogen peroxide form combinations that can be exploded by heat or shock. Contaminants in hydrogen peroxide affect the decomposition rate and shock sensitivity. Proper stabilizers such as pyrophosphates, fluorides, cyanides, and sodium stannate can be used to control the rate of decomposition.

Materials of Construction

Proper selection and passivation of materials are essential when handling hydrogen peroxide because of the possibility of explosive combinations. Two important factors must be considered in choosing a material. They are 1) effect of hydrogen peroxide on the material and 2) the effect of the material on hydrogen peroxide. Materials have been divided into 4 service classes, as follows:

I. Long time contact

Aluminum 1060	Teflon
Tantalum (pure)	Zirconium (pure)

II. Transient contact and temperature limitations as experienced in valves and pumps.

Aluminum 3003, 4043, 5052, 5254, 6061

Stainless Steel 304, 316, 321, 347, 17-7PH

III. Materials that might contaminate the hydrogen peroxide and render it unsuitable for storage for even short time contact experience in one shot propulsion units.

Aluminum 2024, Stainless Steel 19-9 DL, Hastelloys,
Inconel X

IV. Material causing rapid decomposition, are quickly attacked by it, or forms explosive mixture.

Stainless Steel (400 series)	Mild Steel
Cobalt	Copper
Magnesium	Titanium
Nickel	Beryllium

Monomethylhydrazine CH_3NHNH_2:

Chemical

Boiling Point	189.5^{o}F
Freezing Point	-62.5^{o}F
Critical Temperature	562^{o}F
Critical Pressure	1180 psig

Monomethylhydrazine is a strong reducing agent, weakly alkaline, and when exposed to air on a large surface may undergo auto-ignition. A film of monomethylhydrazine in contact with metallic oxides or other oxidizing agents may cause ignition. It will decompose when in contact with some metals such as iron, copper, and their alloys. Monomethylhydrazine is insensitive to friction and impact, contracts upon freezing and is not chemically affected by freezing.

Materials of Construction

Monomethylhydrazine is compatible with most common metals under a wide variety of conditions. The preferred materials are:

Stainless Steel 304 and 347

Aluminum 3003, 5052, 5154, 1060, 6061

Due to the diversified applications of non-metals, it is impractical to be specific about their performance. However, the preferred materials are:

Teflon

Kel-F (unplasticized)

Polyethylene (high density)

Fuming Nitric Acids:

Chemical

The fuming nitric acids considered are:

WFNA - white fuming nitric acid

RFNA - red fuming nitric acid

INFNA - inhibited white fuming nitric acid

IRFNA - inhibited red fuming nitric acid

	WFNA	RFNA
Bubble Point	$186^{o}F$	$150^{o}F$
Melting Point	$-45^{o}F$	$-57^{o}F$

The bubble point is the temperature at which nitric acid appears to boil. Fuming nitric acids are highly corrosive oxidizing agents and will vigorously attack metals. They also react with organic materials spontaneously causing fires. They are stable to all types of mechanical shock and impact. All corrosion rates, susceptibility to corrosion, and reaction rates with fuels are affected by temperature. To reduce the corrosion rate and susceptibility to corrosion in some applications an inhibitor of hydrofluoric acid may be added to fuming nitric acid.

Materials of Construction

Metals acceptable for use are:

Aluminum 1060	below 160°F
3003	below 130°F
3004	below 150°F
6061	below 160°F
5254	below 160°F
5052	below 160°F
Tantalum	below 160°F
Zirconium	below 160°F
Haynes 25	below 160°F
Nickel A	below 130°F
Stainless Steel 347	below 130°F
19-9DL	below 130°F
304ELC	below 130°F
321	below 130°F
303	below 130°F
316	below 120°F

Other ferrous and non-ferrous metals and their alloys are not acceptable because they react with fuming nitric acid, producing toxic oxides of nitrogen, and fail due to corrosion.

Non-metals acceptible for use are:

Kel-F, Teflon, Polyethylene

Nitrogen Tetroxide:

Chemical

Boiling Point	$70^{o}F$
Freezing Point	$11^{o}F$
Critical Temperature	$316.8^{o}F$
Critical Pressure	1455 psig

Nitrogen tetroxide is a corrosive oxidizing agent that is hypergolic with monomethylhydrazine. It is insensitive to mechanical shock, heat, and detonation and is inflammable in air but does support combustion. Nitrogen tetroxide vapors form explosive mixtures with fuel vapors, especially in confined spaces. At temperatures above $302^{o}F$ dissociation into nitric oxide and free oxygen begins.

Materials of Construction

At standard ambient temperatures and pressures, nitrogen tetroxide is not corrosive to most common metals. The degree and susceptibility of corrosion is influenced by the moisture content.

Metals acceptible for use are:

1) For dry (less than 0.1% water) nitrogen tetroxide

Aluminum alloys	low alloy steels
Stainless steel	titanium (if water content is increased N_2O_4 may become shock sensitive)

2) For wet nitrogen tetroxide

Aluminum alloys	alloy steels
Stainless steel (300 series)	

Metals not recommended for use with nitrogen tetroxide are:

Copper alloys, nickel alloys

Non-metals suitable for handling nitrogen tetroxide are:

Kel-F(unplasticized)	Polyethylene	short time exposures
Teflon	Silicone rubber	

Vinyl plastics, in general, do not hold up in N_2O_4.

Liquid Oxygen:

Chemical

Boiling Point	-297.4
Freezing Point	-361
Critical Temperature	-181.1
Critical Pressure	722.2 psig

Oxygen is a strong oxidizer which vigorously supports combustion and is next to fluorine in reactivity. Although the reactivity of liquid oxygen is relatively low compared to oxygen at room temperatures, it will not decompose and mixes with all materials that will burn, especially rocket fuels, representing explosion hazard. These mixtures can usually be exploded by static electricity, mechanical shock, electric spark, and other similar energy sources.

Materials of Construction

The primary consideration in selecting a material is its ability to withstand low temperatures without losing its mechanical properties and to withstand stress concentrations developed during sudden or large temperature changes. Ferrous alloys (except 18-8 and Ni series) are too brittle for use at liquid oxygen temperatures. The metals acceptable for service with liquid oxygen are:

Stainless steel (18-8 series)	Brass	Inconel
Copper	Monel	Aluminum
Bronze	Nickel	

Several instances have been reported of violent reactions of titanium and liquid oxygen which appeared to be related to impact. Impact studies have also shown some reactivity of oxygen with zirconium and aluminum.

Non-metals approved for LOX are:

Teflon, Kel-F, Special silicone rubbers

Organic materials should be avoided with both liquid and gaseous oxygen because of possible explosions. If use is necessary caution should be taken. Fluorocarbons and aluminum should not be used together in the system handling liquid oxygen.

Pentaborane (B_5H_9):

Chemical

Boiling Point	140.1°F
Freezing Point	-52°F
Critical Temperature	441°F
Critical Pressure	557 psig

Pentaborane may flame spontaneously on contact with air, and may react explosively or form shock-sensitive solutions with highly halogenated or oxygenated solvents. By itself pentaborane is insensitive to shock. It will react with hydrazine and other amines, and decomposes at 302°F but not explosively.

Materials of Construction

Metals and alloys suitable for use are:

Aluminum 5052, 6061-T6, 7075-T6, 2024-T3, 3003-H14

Stainless steel 18-8 series	Nickel
Low carbon steel	Magnesium
K-Monel	Titanium
Monel M-8330-B	Copper, Brass
Hastelloys	

Non-metals suitable for use are

Kel-F, Teflon, Fluorosilicone rubber, Viton

Some of the prohibited materials with pentaborane are:

Natural rubber	Neoprene
Nylon	Silicone
Vinylidene plastic	

Perchloryl Flouride (CLO_3F):

Chemical

Boiling Point	$-52.3^{o}F$
Freezing Point	$-231^{o}F$
Critical Temperature	$203.3^{o}F$
Critical Pressure	764 psig

Perchloryl fluoride is a strong oxidizing agent which under most conditions is relatively non-reactive and stable to $850^{o}F$. Temperature is the major controlling factor in reaction rates. Explosions have been noted as a result of mixing gaseous or liquid perchloryl fluoride with ammonia, hydrazine, and some gaseous or liquid amines. Perchloryl fluoride vapors can form an explosive mixture with combustible vapors that can be detonated by static electricity, electric spark, or flame. It combines with porous organic materials forming shock sensitive explosive mixtures.

Materials of Construction

At room temperatures perchloryl fluoride is not corrosive to most metals but moisture content is a governing factor in selecting a material for service. The readily oxidizing metals will burn in perchloryl fluoride with the metal surface area to volume ratio a major factor. Powders and filings burn readily, while foil and sheet are more resistant. Metals suitable for service are:

Perchloryl Fluoride (dry)	Perchloryl fluoride (moist)
Carbon steel	Stainless steel (304, 310, 314)
Aluminum	Hastelloy
Stainless Steel	Tantalum
Copper	
Brass	
Bronze	

The lack of operational and long term data restricts the non-metals that can be recommended for severe service, where operating conditions might initiate combustion or detonation, to Kel-F and Teflon.

Unsymmetrical Dimethylhydrazine (UDMH):

Chemical

Boiling Point	146°F
Freezing Point	-71°F
Critical Temperature	480°F
Critical Pressure	865 psig

UDMH is slightly alkaline and hypergolic with some oxidants such as fuming nitric acids, nitrogen tetroxide, hydrogen peroxide, chlorine trifluoride, and fluorine. No formation of gums or other solids has been noted even after sustained storage. UDMH is insensitive to shock and has thermal stability up to 480°F. Decomposition in an atmosphere of helium or nitrogen occurs at 740 to 750°F while at one atmospheric pressure, the decomposition becomes explosive at 1112°F.

Materials of Construction

UDMH is compatible with most metals under a wide variety of conditions. There are no known limitations on the use of UDMH with nickel, monel, or stainless steels 303, 304, 316, 321, and 347. Aluminum alloys are good for this service, but it has been noted that aluminum is attacked to some extent by dilute aqueous solutions of UDMH. The use of copper and high-copper alloys is prohibited in UDMH handling systems.

Because of the variable nature of the service in which non-metals may be used, it is impractical to be specific regarding their performance. The best materials include Teflon, unplasticized Kel-F, Nylon and Polyethylene.

Section 5

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